FA01-1 (I) 2627
Optimized S-curve motion profiles for minimum residual vibration
Meckl, Peter H. Purdue Univ.
Arestides, Peter B. Purdue Univ.
Woods, Matthew C. Purdue Univ.

A method for developing optimized point-to-point motion profiles to achieve fast motions with minimum vibration is presented. The proposed approach uses the well-known s-curve motion profiles, but optimizes the selection of the ramp-up (and ramp-down) time. The selection of ramp-up time is based on a frequency analysis that minimizes the excitation energy of the input forcing function at the system natural frequency. Simulation results on a lightly-damped system undergoing point-to-point motions demonstrate that the proposed approach decreases residual vibration by almost an order of magnitude over other approaches, even when the actual natural frequency is in error by 10%.

FA01-2 (I) 2632
Closed-form generation of specified-fuel commands for flexible systems
Mills, Bart W. Massachusetts Inst. of Tech.
Singhose, William E. Massachusetts Inst. of Tech.
Seering, Warren P. Massachusetts Inst. of Tech.

A method for generating on-off command profiles for flexible systems is presented. The command profiles move a system without residual vibration while using a specified amount of actuator fuel. The commands are described by closed-form expressions involving the system parameters. Performance measures such as, move duration, maximum transient deflection, and robustness to modeling errors indicate that the closed-form commands are attractive alternatives to time/fuel optimal commands that must be determined with a numerical optimization.

FA01-3 (I) 2637
Optimal filtering to minimize the elastic behavior in serial link manipulators
Magee, David P. Texas Instruments Inc.
Book, Wayne J. Georgia Inst. of Tech.

This paper presents a new optimal filtering algorithm called the Optimal Arbitrary Time-delay (OAT) filter that has been designed to minimize the elastic behavior in serial link manipulators. However, as the analysis will show, the filtering algorithm can reduce the level of vibration in any system whose elastic motion can be modeled as a set of linear, ordinary differential equations with proportional damping. After analyzing some of the filter properties, experimental results demonstrate just how well the optimal filtering algorithm can minimize vibration.

FA01-4 (I) 2643
Command shaping control of an operator-in-the-loop boom crane
Lewis, Derek Michigan Tech. Univ.
Parker, Gordon G. Michigan Tech. Univ.
Driessen, Brian J. Sandia National Labs.
Robinett III, R. D. Sandia National Labs.

This paper presents a control method for suppressing payload sway caused by operator commanded maneuvers, in rotary boom cranes. The crane configuration studied, consists of a payload mass that swings on the end of a spherical pendulum, which is attached to a boom capable of hub rotation and elevation (luffing). Positioning of the rotary crane is accomplished through the hub and boom angles, and the lift line length. Since the configuration of the crane affects the excitation and response of the lift line, the sway control scheme must account for the varying geometry of the system. Adaptive forward path command filters are employed to remove the components of the command signal which induce oscillation of the lift line. A real-time operator-in-the-loop simulation, is used to demonstrate results for a simultaneous three-axis maneuver.

FA01-5 (I) 2648
Point-to-point control of a MIMO servomechanism
de Roover, Dick SC Solutions Inc.
Sperling, F. B. Philips Research
Bosgra, Okko H. Delft Univ. of Tech.

Many modern mechanical servomechanisms require high precision point-to-point motion of a mass without residual vibration. In a previous publication we showed how residual-free motion could be accomplished for one linear motor of a high-precision servo. In this paper we show how the theory of command shaping for residual free motions can be extended for systems with multiple inputs and outputs.

FA01-6 (I) 2652
Learning input shaping technique for non-LTI systems
Park, Juyi Korea Adv. Inst. of Sci. & Tech.
Chang, Pyung Hun Korea Adv. Inst. of Sci. & Tech.

It is well known that a conventional Input Shaping Technique is not very effective in suppressing residual vibrations for non-LTI systems, such as substantially nonlinear or time-varying systems. In an effort to increase the effectiveness for such systems, this paper presents a Learning Input Shaping Technique (LIST), which iteratively updates the parameters of the IST from the previous trials. Simulations are presented for 4 different cases: (1) when the natural frequency or damping of a system does not estimated well; (2) when a system has time varying vibration; (3) when a system has nonlinear flexibility; and (4) when a closed loop system includes the saturation limit in the loop. The experiments are made by using a six D.O.F industrial robot to evaluate the method. The results of both the simulations and experiments show that the residual vibrations become considerably smaller as iteration goes on, thereby demonstrating the effectiveness of the LIST.

FA02-1 (I) 2657
Polynomial matrix analysis using symbolic computation
Ogunye, Ayowale B. Air Products & Chemicals, Inc.

The polynomial matrix approach of Soderstrom et al. (1996), for the computation of the covariance function of a multivariate ARMA process, is implemented in a symbolic computing system (MapleV) in this paper. Procedures were developed to solve the discrete-time symmetric matrix Diophantine equation and to compute the covariance function of a multivariate ARMA process. This algebraic implementation would have been extremely difficult to carry out in a strict numeric computing environment. The use of MapleV has provided symbolic results quickly and efficiently, with a tremendous gain in time and with minimal effort.

FA02-2 (I) 2662
Generating parameter-dependent linear families from nonlinear dynamics
Kwatny, Harry G. Drexel Univ.
Chang, Bor-Chin Drexel Univ.

Generating families of linear models from nonlinear parameter-dependent equations requires explicit analytical characterization of the equilibrium surface. Doing so in terms of the original system parameters is generally not possible. Introducing an alternative parameterization, we propose an efficient method for computing local linear parameter-dependent families. Although local, these families can be constructed anywhere, specifically around bifurcation points where other methods fail.

FA02-3 (I) *
Experiments with symbolic computation for active noise and vibration control
Ghanadan, Reza Lucent Technologies

FA02-4 (I) 2667

Nonlinear system analysis applied to the numerical conditioning of dynamical models for physical processes

Weiss, M. Tech. Univ. of Eindhoven
Preisig, Heinz A. Univ. of New South Wales

Symbolic manipulation techniques known from nonlinear system theory are applied for solving the problems of consistent initialization and index reduction for a class of high index differential algebraic systems that occur frequently in first principles modelling of physical processes. The approach is illustrated with two concrete examples.

FA02-5 (I) 2672

NL control: a symbolic computation toolbox for nonlinear control by extended linearization

Rodriguez-Millan, Jesus Univ. de Los Andes

In this paper we describe the symbolic computation tool NLControl, a computing aid to automate the design of linear and nonlinear controllers and observers to compensate smooth enough nth order nonlinear dynamical control systems by Jacobian and extended linearization. NLControl is conceptually built upon the decomposition of any mth order linear filter into a generalized kth order input PD-like controller followed by a mth order state-feedback like controller. Such decomposition formally reduces the design of a nonlinear extension of an arbitrary linear filter to the appropriate assembly of two independent design subalgorithms: the former for the design of extended nonlinear state-feedback controllers, and the second for the design of extended PID controllers. These supporting subalgorithms and their symbolic computation implementations using Mathematica® were already described in previous works.

FA02-6 (I) 2677

Modeling and simulation for control design

Salter, Eric Techno-Sciences, Inc.
LaVigna, Chris Techno-Sciences, Inc.
Mattice, Mike Picatinny Arsenal
Devito, Mary Picatinny Arsenal
Testa, Bob Picatinny Arsenal

This paper documents the use of recently developed symbolic software for modeling of a U.S. Army M113 armored personnel carrier and numerical simulation of the generated non-linear ordinary differential equations of motion. A brief discussion of the symbolic software used for modeling, analysis, and control system design of multiple body systems is presented. This software is used to create a thirteen degree of freedom model of the vehicle. Numerical simulations were conducted to evaluate the predicted vehicle response for constant velocity motion over standard terrain profiles and for response to gun recoil disturbance.

FA03-1 2682

Repetitive control experiments for a CD player

Lee, Richard C. H. Univ. of Cambridge
Smith, Malcolm C. Univ. of Cambridge

This paper describes some controller designs and experiments for repetitive control of the radial tracking loop of a Philips CD player. An eccentric test disc was used which generated a periodic disturbance signal. Asymptotic rejection of several harmonics was achieved along with satisfactory robustness and transient performance. The controllers were designed using an H-infinity loop shaping approach.

FA03-2 2685

A new method on repetitive tracking control of electro-hydraulic servo systems

Tang, Xiaoqi Hong Kong Univ. of Science & Tech.
Cai, Lilong Hong Kong Univ. of Science & Tech.
Huang, Weiqing Hong Kong Univ. of Science & Tech.

A new repetitive tracking control scheme for electro-hydraulic servo systems is presented in this paper. For a repetitive task of the system, both input and output signals is approximated by Fourier series (FS) and their functional relationship is expressed by a mapping which is the ratio of their corresponding components in the Fourier space. An iterative algorithm is designed by using a repetitive strategy according to this inverse mapping, output error and input of the last cycle. The experiment results on a plastic injection molding machine show that the proposed controller can improve the performance significantly.

FA03-3 2687

Synthesis and analysis of digital multiple repetitive control systems

Chang, Woo Sok Massachusetts Inst. of Tech.
Suh, Il Hong Hanyang Univ.
Oh, Jae-Hyuk Massachusetts Inst. of Tech.

This paper newly proposes the so-called digital ‘multiple’ repetitive control systems which can regulate efficiently ‘multiple repetitive errors’ which contain multiple dominant fundamental frequencies and their harmonics. Our multiple repetitive controller has not only a very simple structure but also such advantages as smaller memory requirement and faster error convergence speed than the conventional ‘single’ repetitive controller. This paper also presents a robust stability condition and an error convergence condition for our multiple repetitive control systems in a mathematically rigorous way. The performance of our multiple repetitive control system is demonstrated through simulations.

FA03-4 *

Iterative learning control for non-minimum phase systems

Gao, Jianbing Iowa State Univ.
Chen, Degang Iowa State Univ.

FA03-5 2692

Application of repetitive controllers to nonlinear plants

Ghosh, Jayati Univ. of California at Santa Barbara
Paden, Brad Univ. of California at Santa Barbara

Repetitive controllers are generally applied to reject periodic disturbances and track periodic reference signals with a known period. Their design is based on ‘the internal model principle’ proposed by Francis and Wonham. This work applies a finite-dimensional repetitive controller to two different classes of nonlinear plants. Simulation results show asymptotic tracking of the periodic reference signal by the proposed repetitive controller in closed loop up to the Nth harmonic frequency. In this work, we apply repetitive controllers to several classes of nonlinear plants, whereby tracking of periodic reference signals is possible. A proof of robustness of the repetitive control system to small nonlinearities, like actuator nonlinearities has been provided. Further, an industrial application of the proposed controller to the optical turning process is discussed next. For this application a new modified repetitive controller is also presented which can track a quasi-periodic reference signal with a slowly changing amplitude.

FA03-6 2698

Constrained SPSA controller for operations processes

Rezayat, Fahimeh California State Univ.

Continuous quality improvement calls for employing methodologies that assist in continual reduction of variations in process performance characteristics around their target values. In a complex operations process the underlying structure of the process is unknown to the operations managers. Hence, identification of the source of variations and variation reduction are difficult and time-consuming tasks. Under the assumption that the process design is capable of producing products that meet customer’s requirements, the emphasis is on continually improving performance and conformance dimensions of the quality of a complex/nonlinear operations process when there exist almost no knowledge about the process structure. The study considers a case in which some of the process parameters must take values only in pre-specified ranges. It also includes the customer requirements on the product characteristics’ values as constraints in the optimization process. Further, the study employs a penalty function for transforming a constrained optimization to an unconstrained one, along with a neural network feed-forward controller which is based on

simultaneous perturbation stochastic gradient approximation. Simulation findings indicate that the constrained optimization will result in a fewer non-conforming outputs than the unconstrained optimization method.

FA04-1 2703

Algebraic approach to robust controller design: a geometric interpretation

Henrion, Didier — LAAS-CNRS
Sebek, Michael — Czech Academy of Sciences
Tarbouriech, Sophie — LAAS-CNRS

The problem of robust controller design is addressed for a single-input single-output plant with a single uncertain parameter. Given one controller that stabilizes the nominal plant, the Youla-Kucera parametrization of all stabilizing controllers and quadratic forms over Hermite-Fujiwara matrices are used to provide clear and simple geometric answers to the following questions: Can the plant be robustly stabilized by a nominally stabilizing controller? How can this robust controller be designed? Thanks to recent results on bilinear matrix inequalities, this geometric interpretation allows to state the equivalence between robust controller design and the concave minimization problem.

FA04-2 2708

Robust control for uncertain linear systems with constraints on output

Hu, Lisheng — Zhejiang Univ.
Sun, You-Xian — Zhejiang Univ.
Cao, Yong-Yan — Univ. of Hong Kong

The primary disadvantage of current design techniques of robust control is their inability to deal effectively with pre-specified time-domain performances of systems. In this paper we consider robust control for uncertain linear systems with pre-specified time-domain performances, i.e. for such systems with constraints on outputs of systems. Using the practical stability theory, we obtain a design procedure of robust control for uncertain linear systems with constraints on outputs of systems. The sufficient conditions of robust stability for uncertain linear systems with constraints on outputs of systems subject to a bounded exterior disturbance are described by a series of parametric conditions and linear matrix inequalities (LMIs). Then a possible synthesis procedure and a numerical example are discussed.

FA04-3 2713

Practical stabilization of nonlinear uncertain systems without matching conditions

Fei, Shumin — Southeast Univ.
Feng, Chun-Bo — Southeast Univ.

In this paper, the practical stabilization of nonlinear uncertain systems without matching conditions is discussed. The necessary and sufficient conditions of its practical stabilization is given, and we obtain that the bound of the practical stabilization for a class of uncertain systems is independent of the bound of its Liapunov function, but dependent only on the structure of the system itself and the requirements of the designer. Finally, an example is given.

FA04-4 2718

A framework for robustness analysis of constrained finite receding horizon control

Primbs, James A. — California Inst. of Tech.
Nevistic, Vesna — ETH Swiss Fed. Inst. of Tech.

A framework for robustness analysis of constrained finite receding horizon control is presented. We derive sufficient conditions for robust stability of the standard discrete-time linear-quadratic receding horizon control formulation with arbitrary terminal weights. The key is to view stability as an implication between quadratic forms, allowing an application of the S-procedure. Robustness with respect to plant/model mismatch as well as state measurement error is reduced to the feasibility of linear matrix inequalities. Examples demonstrate this approach.

FA04-5 2723

Robust H-infinity state feedback control for generalized parameter uncertain system with time delays in discrete time case

Kim, Jong Hae — Kyungpook National Univ.
Jeung, Eun Tae — Changwon National Univ.
Lee, Sang Kyung — Kyungpook National Univ.
Park, Hong Bae — Kyungpook National Univ.

In this paper, we consider the problem of designing H-infinity state feedback controller for the generalized time delay systems in discrete time case. The generalized time delay system problems are solved on the basis of LMI technique. Using some changes of variables and Schur complement, the obtained sufficient condition can be written as a LMI form in terms of transformed variables. The proposed method can be extended into the problem of robust H-infinity state feedback controller design method easily.

FA04-6 2725

Robust stabilization of singular systems with H-infinity-bounded uncertainty

Su, Qing — Univ. of Hawaii at Manoa
Syrmos, Vassilis L. — Univ. of Hawaii at Manoa

In this paper, the problem of robust stabilizing a linear, time-invariant singular system is studied. The characterization is given in terms of H-infinity-bounded perturbations to the numerator and denominator factors of its normalized left coprime factorization. An optimal stability margin is provided in terms of the definition of the Hankel norm of a singular system. The Hankel norm is computed using two generalized Lyapunov equations.

FA05-1 2730

Filtering and differentiating noisy signals using neural networks

Schmidt, Martin — Darmstadt Univ. of Tech.
Nelles, Oliver — Darmstadt Univ. of Tech.

Measured signals are difficult to differentiate. Measurement noise, quantization and jitter occur and in general cannot be eliminated by simple lowpass filtering. Well known solutions are discrete time derivative and state variable filters. This paper presents a new approach for off-line filtering and differentiating sampled time series using a special kind of neural networks, namely an extension of the local linear model tree (LOLIMOT). The filtered signal can be guaranteed not to leave a given band of tolerance, shows human-like smoothing effects and allows the introduction of a-priori knowledge.

FA05-2 2732

A class of nonlinear filtering problems arising from drifting sensor gains

Vincent, Tyrone L. — Colorado School of Mines
Khargonekar, Pramod P. — Univ. of Michigan

This paper considers a state estimation problem where the nominal system is linear, but the output (sensor) has a time varying gain component. This is a general sensor self-calibration problem, and is of particular interest in the problem of estimating wafer thickness and etch rate during semiconductor manufacturing using reflectometry. We explore the use of a least squares estimate for this nonlinear estimation problem, and give several approximate recursive algorithms for practical realization. Stability results for these algorithms are also given. Simulation results compare the new algorithms with the Extended Kalman Filter (EKF) and Iterated Kalman Filter (IKF).

FA05-3 2737

Machine friction estimation for modeling, diagnostics, and control

Ray, Laura — Dartmouth College
Remine, Jennifer S. — Dartmouth College

This paper describes experiments whose objective is to estimate dynamic friction without relying on measured friction force or a structured friction model. The extended Kalman-Bucy filter based estimator relies on an accurate model of system dynamics and measured motion to extract friction force. The paper motivates and

describes the estimation method and reports results of estimating friction force during unidirectional and bi-directional motion of a sliding contact. Filter-based friction estimation addresses characterization of nonstationary friction due to uncontrollable factors such as wear, normal force variation, and lubricant condition, factors that are difficult to capture with a constant parameter friction model. The method aims to estimate friction force for three purposes: friction modeling, friction-based diagnostics, and friction compensation.

FA05-4 2742

Processing remote sensing data to categorize lake bed surficial substrates

Bonde, John Univ. of Minnesota
Cholwek, Gary Great Lakes Science Center
Li, Xing Univ. of Minnesota
Richards, Carl Univ. of Minnesota
Yin, K. Karen Univ. of Minnesota

To categorize spawning and nursery habitat for lake trout in Minnesota's nearshore waters of Lake Superior, data was collected with a single beam echosounder coupled with a RoxAnn bottom classification sensor. Test areas representative of the different bottom surficial substrates were sampled. The resultant data consisted of acoustic signals that showed both depth and substrate type, and were positional tagged in real-time with DGPS data into a GIS database. To better interpret the output signal from the RoxAnn, several pattern classifiers were developed by multivariate statistical method. A device usable for real-time classification is constructed, which will be of great value to fishery and other natural resource managers.

FA05-5 2744

Square-root information filtering and fixed-interval smoothing with singularities

Psiaki, Mark L. Cornell Univ.

The square-root information filter and smoother algorithms have been generalized to handle singular state transition matrices and perfect measurements. This has been done to allow the use of SRIF techniques for problems with delays and state constraints. The generalized algorithms use complete QR factorization to isolate deterministically known parts of the state and nonsingular parts of the state-transition and disturbance-influence matrices. These factorizations and the corresponding changes of coordinates are used to solve the recursive least-squares problems that are basic to the SRIF technique.

FA05-6 2749

Controlling target estimate covariance in centralized multisensor systems

Kalandros, Michael Univ. of Colorado
Pao, Lucy Y. Univ. of Colorado

Current multisensor fusion tracking systems can be easily overwhelmed by incoming data, especially as the number of targets and sensors increases. Sensor management schemes have been proposed to reduce the computational demand of these systems while minimizing the loss of tracking performance. This paper presents a system that will maintain a desired covariance level for each target while reducing the resource demands on the tracking system. Other functions performed by a sensor manager like prioritizing and scheduling are assumed to be done elsewhere, but result in delays in the execution of sensing requests made by the system. Three sensor selection algorithms are presented based on different resource and performance metrics and show a dramatic improvement over "dumb" sensing systems in simulation. Execution delay is shown to have a deleterious effect on the tracking performance of the system, but most of that performance can be restored when a prediction algorithm is used to model the delay.

FA06-1 2754

Uncertainty model unfalsification with simulation

Woodley, Bruce R. Stanford Univ.
Kosut, Robert L. SC Solutions
How, Jonathan P. Stanford Univ.

There has been much recent interest in model unfalsification for robust control of dynamic systems. In particular, it has been shown how to establish a tradeoff between sensor/process disturbances and linear time-invariant dynamic uncertainty using prediction error modeling. Unfalsification has also been integrated into adaptive control algorithms, in which a key component is the ability to trade between disturbances and dynamic uncertainty. The main contribution presented here is the calculation of model unfalsification tradeoff curves for a simple simulated system. The unfalsified dynamic uncertainties are compared to the difference between the identified models and the true model.

FA06-2 2756

An optimal two stage identification algorithm for Hammerstein-Wiener nonlinear systems

Bai, Er-Wei Univ. of Iowa

An optimal two stage identification algorithm is presented for Hammerstein-Wiener systems where two static nonlinear elements surround a linear block. The proposed algorithm consists of two steps: The first one is the recursive least squares and the second one is the singular value decomposition of two matrices whose dimensions are fixed and do not increase as the number of the data point increases. Moreover, the algorithm is shown to be convergent in the absence of noise and convergent with probability one in the presence of white noise.

FA06-3 2761

Identification and design of time varying system

Tsumura, Koji Chiba Univ.
Kimura, Hidenori Univ. of Tokyo

In this paper, we analyze system uncertainty of time varying systems caused by identification of the least squares method. The errors between identification models and true systems at each time are investigated and we show that the radius of each corresponding uncertainty can be calculated in a statistical sense. The results are also applied to a design of closed loop systems by the gain scheduling for LPV systems.

FA06-4 2766

Performance analysis of N4SID state-space system identification

Flint, T. W. Univ. of Rhode Island
Vaccaro, R. J. Univ. of Rhode Island

This paper describes a statistical performance analysis method for multi-variate subspace system identification algorithms. The analysis is based on a recently developed perturbation expansion of the singular value decomposition. We demonstrate the technique by analyzing the numerical state-space subspace system identification algorithm N4SID. An expression for the variance of the identified eigenvalues based on a finite record of input/output data is derived and verified using MATLAB simulations.

FA06-5 2768

An identification method for a class of linear time-varying systems

Feng, Chun-Bo Southeast Univ.
Yin, Bin Southeast Univ.

In this paper a new method for identifying TV systems is proposed, which is based on making use of time-variation characteristics of system parameters. By preprocessing the original system, we transform the identification for TV systems into that for piecewise TI systems. The boundedness of this algorithm is discussed and simulation results show its good tracking ability.

FA06-6 2770

LMS identification of systems with dynamics and an output deadzone

Rekow, Andrew Stanford Univ.
Jones, Vincent K. Stanford Univ.
Parkinson, Bradford W. Stanford Univ.

A system that extends traditional FIR filter adaptive system identification and control for use with systems that include an actuator deadzone has been developed. This method automatically identifies both the system's dynamic and deadzone components. Nearly optimal performance is achieved utilizing a modified version of the Least Mean Square error minimization scheme. From the identified model, a stable feedforward inverse controller that linearizes the system is quickly and reliably obtained.

FA07-1 2775
Stabilization of an electromagnetically controlled oscillator
Hong, Jeongho — Univ. of Michigan
Cummings, Ian A. — Univ. of Michigan
Bernstein, Dennis S. — Univ. of Michigan
Washabaugh, Peter D. — Univ. of Michigan

In order to examine the problem of deforming a membrane into a paraboloidal shape by means of electrostatic forces, we consider a mass-spring system with electromagnetic actuation. We show that if the equilibrium gap is less than two-thirds of the relaxed gap, then the equilibrium is unstable. We then derive and compare controllers that stabilize these unstable equilibria and consider the actuator requirements needed to effect stabilization. Finally, several controllers are implemented on a control experiment involving an electromagnetically controlled oscillator.

FA07-2 2780
The instability of last-buffer-first-serve scheduling policy for capacitated re-entrant lines
Reveliotis, Spyros A. — Georgia Inst. of Tech.

This paper demonstrates through an example, that the Last-Buffer-First-Serve scheduling policy is unstable, when applied on re-entrant lines with finite buffering capacity. The issue is important because, contrary to typical modeling assumptions, all contemporary production systems operate under substantial buffering capacity constraints. Moreover, as these environments advance towards higher levels of material-handling automation, the effect of these constraints on the system operation will continuously increase.

FA07-3 2785
A topological obstruction to global asymptotic stabilization of rotational motion and the unwinding phenomenon
Bhat, Sanjay P. — Indian Inst. of Tech.
Bernstein, Dennis S. — Univ. of Michigan

We show that a continuous dynamical system on a state space that has the structure of a vector bundle on a compact manifold possesses no globally asymptotically stable equilibrium. This result is directly applicable to mechanical systems having rotational degrees of freedom. In particular, the result applies to the attitude motion of a rigid body. In light of this result, we explain how attitude stabilizing controllers appearing in the literature lead to unwinding instead of global asymptotic stability.

FA07-4 2790
Relationships between input-output stability and exponentially stable periodic orbits
Chung, Chung Choo — Hanyang Univ.
Hauser, John — Univ. of Colorado

In this paper, we present new results concerning the relationships between the input-output and Lyapunov stability of nonlinear system possessing a periodic orbit. Definition of small-signal finite-gain L-p stability around periodic orbit is introduced. We show L-p stability of exponentially stable periodic orbit using quadratic Lyapunov functions for the periodic orbit. The L-2 gain analysis is presented with Hamiltonian-Jacobi inequality along with an example.

FA07-5 2795
Output stabilizability of periodic systems: necessary and sufficient conditions
Colaneri, Patrizio — Politecnico di Milano
de Souza, Carlos E. — Univ. of Newcastle
Kucera, Vladimir — Czech Academy of Sciences

In this paper the output stabilization problem for linear periodic systems is considered, both in discrete and in continuous time. Necessary and sufficient conditions are derived in terms of periodic differential (or difference) matrix equations. The case when the system is time-invariant is finally discussed.

FA07-6 2797
On parametric stability margin maximization using state feedback pole assignment
Hu, Ting-Shu — Univ. of Waterloo
Lam, James — Univ. of Hong Kong

In this paper, the maximization of the parametric stability margin of state-space uncertain systems under the constraints of pole assignment is investigated. The class of systems considered is where the uncertainty may be modelled as the, possibly nonlinear, variation of a parameter appearing in the entries of the system and input matrices. The continuity and differentiability of the stability margin are discussed. A gradient-based procedure is formulated for the maximization of the stability margin with the corresponding gradient provided. Numerical examples are used to illustrate the technique.

FA08-1 2802
Primal-dual quadratic programming approach to multiple conflict resolution
Oh, Jae-Hyuk — Massachusetts Inst. of Tech.
Feron, Eric — Massachusetts Inst. of Tech.

This paper considers a multiple conflict resolution problem for air traffic control systems. The time required to optimally solve aircraft conflicts is known to grow exponentially with the number of aircraft involved and may become prohibitive when large numbers of aircraft are involved. As an attempt to circumvent this issue, a heuristic polynomial-time conflict resolution algorithm is proposed on the basis of analysis results on the relationship between primal and dual quadratic programs.

FA08-2 2807
Safety certification of air traffic conflict resolution algorithms involving more than two aircraft
Oh, Jae-Hyuk — Massachusetts Inst. of Tech.
Feron, Eric — Massachusetts Inst. of Tech.

Many future air traffic control tasks will require on-line safety-critical optimization algorithms. Among these tasks, real-time air traffic conflict resolution involving more than two aircraft is one of the most challenging. Air traffic control systems based on on-line optimization algorithms must face safety-certification issues such as guaranteed feasibility and guaranteed time of computation. This paper deals with the question of guaranteed feasibility and presents an initial effort at developing an off-line procedure to prove the safety of such an algorithm. The procedure is based on convex optimization technology combined with the so-called S-procedure.

FA08-3 2812
An efficient optimization technique for image restoration
Maryak, John L. — Johns Hopkins Univ.

The Gibbs sampler of Geman and Geman is a standard technique for image restoration. We implemented a similar estimation technique based on a new optimization method (SPSA). Preliminary tests of our results show comparable performance to the Gibbs sampler but with faster running times.

FA08-4 2814
On solving semidefinite programming by quantifier elimination
Anai, Hirokazu — Fujitsu Laboratories, Ltd.

Many control problems and design specifications are described by using matrix inequalities. We focus on a linear matrix inequality (LMI) problems. A number of important problems can be reduced to the

optimization problems of minimizing a linear objective function subject to LMI constraints. This is called "semidefinite programming (SDP)". SDP problems are usually solved numerically as convex optimization problems. But when we consider the real parametric uncertainties the problems often become non-convex and those numerical methods does not work. Therefore, it is desirable to develop the methods which also work for non-convex and parametric case. The Quantifier Elimination (QE) method can deal with parametric case and also does not suffers from non-convexity since it does not utilize "convexity". We present a new symbolic method based on QE for the SDP problems and show some results of experiment by using existing QE package to demonstrate the capability of the method. Due to the great practical complexity of QE procedure, currently the method is practically applicable to moderate size problems. However, compared with existing (numerical) methods for SDP problems the QE based method has many merits as follows; (1) non-convex and (2) parametric case can be dealt with, (3) easy to handle domain restricted and parameter uncertainty, and (4) produce exact answer and check the infeasibility exactly.

FA08-5 2819
Optimization of a class of linear time-periodic systems: a new approach via transformation to a canonical form
Agrawal, Sunil K. Univ. of Delaware
Xu, Xiaochun Univ. of Delaware

This paper addresses optimization of commutative time-periodic linear systems steered by a single input. In this paper, the time-periodic dynamic equations are transformed to a canonical form, referred to as the higher-order form, such that the states and control inputs can be written as higher derivatives of a single variable. This higher-order form is then used to eliminate the dynamic equations explicitly from the optimization problem. It is shown in this paper that for a system with n states and a single input, the optimal solution satisfies a 2nth order differential equation in a single variable along with 2n boundary conditions on higher derivatives of this variable split between the two end time. This differential equation can be solved numerically in an efficient way using weighted residual methods. It is also shown here that for a set of problems using this method, closed-form solution is possible. It is impossible to achieve these closed form solutions using conventional methods.

FA08-6 2824
Randomized algorithms for a certain real mu computation problem
Yoon, Albert Univ. of Michigan
Khargonekar, Pramod P. Univ. of Michigan

In this paper, we apply several random search algorithms to a very special mu computation problem posed by Zhu, Huang, and Doyle. The problem is NP hard and so different algorithms which compute solutions effectively are being investigated. The effectiveness of the randomized algorithms is assessed by running them on exactly the same examples used in the paper of Zhu, Huang, and Doyle and comparing the results with those obtained by their branch and bound algorithm. In particular, we present one simple random search algorithm which provides good estimates to the solution with reasonable computation times.

FA09-1 (I) 2829
Non-fragile controller design: an overview
Dorato, Peter Univ. of New Mexico

In this paper we give an overview of non-fragile controller design for linear systems. The controller fragility problem is basically the problem of performance deterioration of a feedback control system due to inaccuracies in controller implementation. The literature on the fragility problem is reviewed and methods for designing non-fragile controllers are summarized. Papers presented on the subject in this invited session are also summarized.

FA09-2 (I) 2832
How to escape from the fragility trap
Kaesbauer, Dieter DLR Oberpfaffenhofen
Ackermann, Juergen DLR Oberpfaffenhofen

The inverted pendulum is used as an example to illustrate controller fragility under minimum norm state feedback. The stabilization process gets trapped in a cusp. A parameter space representation shows a safe escape.

FA09-3 (I) 2837
Robust resilient dynamic controllers for systems with parametric uncertainty and controller gain variations
Haddad, Wassim M. Georgia Inst. of Tech.
Corrado, Joseph R. Georgia Inst. of Tech.

A feedback control design problem involving structured plant parameter uncertainties and controller gain variations is considered. Specifically, the robust fixed-structure guaranteed cost controller synthesis framework is extended to address the design of robust resilient fixed-order (i.e., full- and reduced-order) dynamic controllers for systems with structured parametric uncertainty and controller gain uncertainty. Several examples are provided which clearly demonstrate the need for robust resilient control.

FA09-4 (I) 2842
Robust, non-fragile and optimal controller design via linear matrix inequalities
Jadbabaie, Ali California Inst. of Tech.
Abdallah, Chaouki T. Univ. of New Mexico
Famularo, D. Univ. della Calabria
Dorato, Peter Univ. of New Mexico

In this article, we introduce a robust, non-fragile state-feedback controller which is also optimal with respect to a quadratic performance index, using Linear Matrix Inequalities (LMIs). The uncertainties are assumed to be polytopic, both in the controller gains and the system dynamics. A numerical example is presented to demonstrate the efficiency of this method, and the controller turns out to be robust with respect to the uncertainties in the plant and the controller.

FA09-5 (I) 2847
Control of ATM networks: fragility and robustness issues
Blanchini, Franco Univ. degli Studi di Udine
Lo Cigno, R. Politecnico di Torino
Tempo, Roberto Politecnico di Torino

Recently, communication networks and ATM (Asynchronous Transfer Mode) in particular, received a growing attention in the control community; see e.g., the papers on this topic at the 1997 IEEE Conference on Decision and Control. Several problems have been studied from the control system point of view, including traffic identification with optimization algorithms, adaptive bandwidth estimation, decentralized and robust flow control. In this paper, we continue this line of research studying the problem of robustly controlling the information flow in a single communication channel of an ATM network. We consider a simplified model already existing in literature in which the main features are the existence of a buffer representing the congestion and a delay time in the communication between the source and the destination nodes. We show that searching for optimal control policies are fragile if the delay time is allowed to vary (possibly of an arbitrarily small amount) with respect to the nominal value on which the design is based. Subsequently, we suggest a classical design procedure which is robust with respect to variations in the delay which does not exceed a prescribed upper bound.

FA09-6 (I) 2852
Stability margins and digital implementation of controllers
Keel, Lee H. Tennessee State Univ.
Bhattacharyya, Shankar P. Texas A&M Univ.

This paper investigates the robustness and related behaviour of control systems containing a digital implementation of a designed continuous time controller, mainly through examples. We determine the coefficient stability margin of the digital controller as the sampling time is varied. We also study the stability and intersample response of the hybrid system as the sampling period varies. The main general

trend indicated by the examples are a) that the stability margin of the digital controller often decreases as the sampling frequency increases and b) that the actual hybrid system may exhibit unstable intersample behaviour even though the discrete time stability margin of the digital controller may be large especially at low sampling frequencies. These examples raise a number of issues related to digital implementation of controllers.

FA10-1 2857
On the use of on-line approximators for sensor fault diagnosis
Vemuri, Arun T. Southwest Research Inst.
Polycarpou, Marios M. Univ. of Cincinnati

This paper describes a sensor fault diagnosis algorithm for a class of nonlinear dynamic systems. The main idea behind this approach is to monitor the closed-loop system for any off-nominal system behavior due to sensor faults utilizing a nonlinear on-line approximator with adjustable parameters. A nonlinear estimation model and learning algorithm are described so that the on-line approximator provides an estimate of the sensor fault. The robustness, stability and learning performance properties of the nonlinear sensor fault diagnosis scheme are established.

FA10-2 2862
Failure detection methods to predict loss of control involving human-interface devices: part I, theory
Repperger, Daniel W Wright Patterson Air Force Base
Haas, M. W. Wright Patterson Air Force Base
Schley, P. C Systems Research Laboratories
Koivo, A. J. Purdue Univ.

A method is developed to detect a precipitation or loss of control in a device used as a human interface. The human-machine problem of interest involves two aircraft engaged in a position tracking scenario. The detection system developed here can be used on-line in real time or can be used in a post hoc sense for analysis of data already collected. This Part I paper discusses the basic theory underlying the operation of such a device.

FA10-3 2867
Nonlinear decoupling approach to fault isolation in linear systems
Garcia, Efrain A. Gerhard-Mercator Univ. of Duisburg
Seliger, Ralf J. Gerhard-Mercator Univ. of Duisburg
Frank, Paul M. Gerhard-Mercator Univ. of Duisburg

The problem of detection and isolation of multiplicative faults in linear systems by using observer-based approaches is considered. The proposed approach is based on a nonlinear decoupling transformation and a nonlinear observer-based residual generation. Existence conditions are explored and a design procedure is provided. An example is used to illustrate the above ideas.

FA10-4 2872
Fault diagnosis and accommodation in dynamic systems: application to a DC motor
Sauter, Dominique D. J. Univ. Henri Poincare-Nancy 1
Hamelin, Frederic Univ. Henri Poincare-Nancy 1
Noura, Hassan Univ. Henri Poincare-Nancy 1

In this paper a method for fault diagnosis and accommodation in dynamic systems is presented. The proposed approach is composed of two steps. In the event of a fault, the first step is the detection of the failed component, and the estimation of the fault parameters. For this purpose an adaptive state observer is used. The second step consists in the design of an adaptive control structure which implicitly reconfigures the control law using the on-line estimates of the altered system dynamics. The application to a DC motor is presented to illustrate the proposed approach.

FA10-5 2874
Neural state estimators for direct model-based fault diagnosis
Alessandri, A. CNR-IAN National Research Council
Parisini, Thomas DEEI-Univ. of Trieste

A model-based fault-detection scheme for nonlinear systems is proposed in this paper, basing on finite-memory state estimation. The faults are diagnosed by means of the estimates of the fault vector (used to describe plant, actuator, and sensor faults). The fault finite-memory estimator is stated in a general nonlinear setup and the optimal functions solving the estimation problem are approximated by means of feedforward neural nets. The optimization of the neural weights consists of two phases. In the first one, any possible “a priori” knowledge on the statistics of the random variables is used to “initialize” (off line) the neural estimation functions. In the second, the optimization (or training) continues on line. Both off-line and on-line phases rely upon stochastic approximation algorithms.

FA10-6 2879
Fault detection, diagnosis and accommodation of dynamical systems with actuator failures via on-line approximators
Demetriou, Michael A. Worcester Polytechnic Inst.
Polycarpou, Marios M. Univ. of Cincinnati

A general framework for the detection, diagnosis and accommodation of a class of actuator faults is developed. This framework, which addresses both abrupt and incipient faults, utilizes a nonlinear adaptive detection observer along with an on-line approximation scheme for failure assessment. The actuator failure is modeled by an additive perturbation of the actuator signal (actuator gain) that is described by a nonlinear function of both the input and output signals. Robust adaptive schemes are introduced to account for modeling errors that affect the diagnosis process and may cause false alarms. Numerical studies for a second-order system using a neural network-based on-line approximator are presented to demonstrate the applicability of the proposed automated diagnostic scheme.

FA11-1 2884
Time-varying linear system decomposed control
Loukianov, Alexander G. CINVESTAV IPN
Utkin, Vadim I. Ohio State Univ.

This paper is concerned with the block control decomposition method for multivariable time varying linear plants in which the control law synthesis problem is divided into a number of sub-problems of lower dimension which can be solved independently. First the block modal control problem is solved. Then to render the approach practicable for a wider range of plants, an observer is also designed using a Lyapunov technique.

FA11-2 2889
Synthesis of time-varying bandwidth filters based on all-pole LTI prototypes
Zhu, J. Jim Louisiana State Univ.
Mickle, M. Chris Louisiana State Univ.

This paper presents a systematic procedure for synthesizing a class of time-varying bandwidth (TVB) filter using a Parallel D-eigenvalue concept and a stability criterion for linear time varying (LTV) systems. Time-varying frequency response of the TVB filter is analyzed and a computable procedure is used to obtain "time-varying Bode plots." Comparisons are made with LTI filters with or without limiter to demonstrate the advantages of the TVB filter. While the procedure is presented for nth-order single-input-single-output lowpass filters based on all-pole LTI prototypes, extension of the results to more general cases are addressed. Application for tracking command shaping filters, implementation of pseudo-differentiators, pseudo-inverse of nonlinear dynamics and nonlinear asymptotic state observers are also discussed.

FA11-3 2895
Application of adaptive controllers to a solar power plant using a multi-model description
Pickhardt, R. Ruhr-Univ. of Bochum

This paper presents the application of indirect adaptive controllers, using different dynamical models for the respective operating-points,

to the distributed collected field of a solar power plant at the Plataforma Solar de Almeria (Spain). The operating-point of the plant together with the actual dynamical model, which is used by the adaptive controller to calculate the new value of the manipulated signal, was selected by a characteristic value determined from measurements of the plant. LQG- and GPC-type adaptive controllers, with and without integrator in the control law, were tested during the experiments. The different operating-points of the plant have been modeled by linear 3rd-order ARMAX models with different discrete dead-times.

FA11-4 2900

Performance with regulation constraints

Stoorvogel, Anton A. Eindhoven Univ. of Tech.
Saberi, Ali Washington State Univ.
Sannuti, P. Rutgers Univ.

We study the problem where we have a regulation (asymptotic tracking) requirement together with a performance requirement. Typically we measure performance by the H2 or H-infinity norm of a chosen transfer function matrix although any other norm such as the L1 norm could be used. In the case when the performance is measured by the H2 norm, there is no loss in performance due to the regulation constraint. On the other hand, when the performance is measured by the H-infinity norm, there exists in general certain loss of performance due to the regulation constraint, and we explicitly characterize such a loss in terms of a static optimization problem.

FA11-5 2905

A set of discrete-time linear systems which has a common Lyapunov function and its extension

Mori, Yoshihiro Kyoto Inst. of Tech.
Mori, Takehiro Kyoto Inst. of Tech.
Kuroe, Yasuaki Kyoto Inst. of Tech.

The common Lyapunov function problem which we study here, is to find a set of systems which has a common quadratic Lyapunov function guaranteeing asymptotic stability of every member system. For both continuous-time and discrete-time systems, some sets having this property have been known. These results run parallel with each other. The aim of this report is to complete this parallelism by providing the discrete-time counterpart for a recently obtained continuous-time result. We show that a set of discrete-time systems has a common quadratic Lyapunov function if every system matrix is transformed into complex triangular matrices by a common complex nonsingular matrix. The obtained class includes the known results. We also show an attempt to enlarge the obtained class.

FA11-6 2907

A stability property of nonlinear sampled-data systems with slowly varying inputs

Lawrence, Douglas A. Ohio Univ.

A stability analysis is presented that deals with the response of a nonlinear sampled-data system to a slowly varying input signal. The main result is similar to existing results for purely continuous-time and discrete-time systems.

FA12-1 2912

Robust stability of nonlinear hydraulic servo systems using closest Hopf bifurcation techniques

Kremer, Gregory G. Univ. of Cincinnati
Thompson, David F. Univ. of Cincinnati

A critical evaluation of current methods for analyzing hydraulic servo systems indicates a need for alternative methods that are better able to quantify robust stability, especially with respect to the existence of nonlinear oscillations. The purpose of this paper is to address that need by examining a new analysis method that is capable of predicting stability robustness for nonlinear systems with high-dimensional parameter spaces. The method is based on the computation of "closest" Hopf bifurcations which correspond to the birth of limit cycle oscillations. A formal procedure that makes use of closest Hopf bifurcations for analyzing the robust stability of nonlinear systems is presented and applied. Practical implementation issues are addressed, with emphasis on interpretation of results to yield a meaningful quantitative measure of stability robustness. The new analysis method is validated via comparisons with previously published describing function results and new simulation results. In all cases, the results from the closest Hopf bifurcation method compare favorably with the baseline results.

FA12-2 2917

Nonlinear fuzzy control on a hydraulic servo system

Zhao, Yongqian Ecole de Tech. Superieure
LeQuoc, Sinh Ecole de Tech. Superieure
Saad, Maarouf Ecole de Tech. Superieure

Hydraulic position servo systems are commonly used in industry. This kind of system is nonlinear in nature and generally difficult to control. The ordinary linear constant gain controller will cause overshoot or even loss of system stability. Application of fuzzy logic controller to a nonlinear hydraulic servo system is investigated in this paper. The dynamic model of the system is given and the stability is also analyzed using Kriging approximation method and Popov's criterion. The steady state error can be eliminated with dead band nonlinearity using this fuzzy controller combined with an integration term. Simulation results show the performance of the fuzzy controller with fast response and less overshoot.

FA12-3 2922

Nonlinear control of a reusable rocket engine for life extension

Lorenzo, Carl F. NASA Lewis Research Ctr.
Holmes, Michael Scott Pennsylvania State Univ.
Ray, Asok Pennsylvania State Univ.

This paper presents the conceptual development of a life-extending control system where the objective is to achieve high performance and structural durability of the plant. A life-extending controller is designed for a reusable rocket engine via damage mitigation in both the fuel (H2) and oxidizer (O2) turbines while achieving high performance for transient responses of the combustion chamber pressure and the O2/H2 mixture ratio. The design procedure makes use of a combination of linear and nonlinear controller synthesis techniques and also allows adaptation of the life-extending controller module to augment a conventional performance controller of the rocket engine. The nonlinear aspect of the design is achieved using nonlinear parameter optimization of a prescribed control structure. Fatigue damage in fuel and oxidizer turbine blades is primarily caused by stress cycling during start-up, shutdown, and transient operations of a rocket engine. Fatigue damage in the turbine blades is one of the most serious causes for engine failure.

FA12-4 2927

Nonlinear control of electrostatically shaped membrane with state and control constraints

Kolmanovsky, Ilya V. Ford Motor Co.
Miller, Robert H. Univ. of Michigan
Washabaugh, Peter D. Univ. of Michigan
Gilbert, Elmer G. Univ. of Michigan

A control scheme for electrostatically shaping a membrane is developed. The scheme achieves stabilization of the first mode of the membrane at a desired equilibrium, that may be open loop unstable, without violating specified state and control constraints. The ideas on the use of an "equilibrium-parametrized" family of Lyapunov functions to enforce state and control constraints in nonlinear systems go significantly beyond the specific example treated here. They can be widely applied in the context of Lyapunov-based designs, including nonlinear systems with disturbance inputs and uncertainties.

FA12-5 2932

L2-gain performance analysis for nonlinear robust visual servo control

Maruyama, Akira Japan Advanced Inst. of Sci. & Tech.
Fujita, Masayuki Japan Advanced Inst. of Sci. & Tech.

In this paper, we deal with disturbance attenuation property of an asymptotically stable nonlinear controller for the visual servo systems. First, based on Lyapunov stability theory, we propose the exponentially stable controller without the external disturbances. Next, we show that the controller achieves disturbance attenuation in the L2-gain sense; that is, the L2-gain of the closed loop system can be made sufficiency small with a suitable selection of the feedback gains. Finally, the usefulness of the controller and the L2-gain performance analysis are confirmed by experiments using an industrial manipulator.

FA12-6 2937
Lyapunov based draw resonance controller for polymer sheet extrusion
Nizami, J. — Univ. of Akron
Batur, Celal — Univ. of Akron

The draw resonance instabilities limit the production speeds of sheet extrusion processes. We propose a nonlinear controller that eliminates the instability at high draw ratios. The controller is derived using the nonlinear process model and Lyapunov based design methodology.

FA13-1 (I) 2942
Implementation of advanced process control - perspectives from industry
Downs, James J. — Eastman Chemical Co.
Ogunnaike, Babatunde A. — DuPont CS&E
Muske, Kenneth R. — Villanova Univ.

Industry can derive significant benefit from successful collaboration with academic research groups in the implementation of advanced process control. A successful collaboration results in an industrially applicable solution to a relevant problem within a reasonable time frame. In order to realize a successful outcome, a number of issues must be addressed prior to initiating a collaboration. Balancing the benefits and concerns along with the issues of publication and the focus of the academic contribution are discussed in this paper.

FA13-2 (I) 2944
Implementation of advanced process control - perspectives from academia
MacGregor, J. F. — McMaster Univ.
Georgakis, Christos — Lehigh Univ.
Muske, Kenneth R. — Villanova Univ.

A successful collaboration between academia and industry in the implementation of advanced process control is one that develops new theory or methodology and also addresses a relevant industrial problem. Collaboration can provide significant benefits to an academic research group. However, there are a series of issues that must be addressed for the interaction to be successful. These benefits and issues are discussed in this paper.

FA13-3 (I) *
Panel Discussion

FA13-4 (I) 2946
Implementation of model predictive control on a hydrothermal oxidation reactor
Muske, Kenneth R. — Villanova Univ.
Dell'Orco, Phillip C. — Los Alamos National Lab.
Le, Loan A. — Los Alamos National Lab.
Flesner, Raymond L. — Los Alamos National Lab.

This paper describes the model-based control algorithm developed for a hydrothermal oxidation reactor at the Pantex Department of Energy facility in Amarillo, Texas. The combination of base hydrolysis and hydrothermal oxidation is used for the disposal of PBX 9404 high explosive. The reactor oxidizes the organic compounds in the hydrolysate solutions obtained from the base hydrolysis process. The objective of the model predictive controller is to minimize the total aqueous nitrogen compounds in the effluent of the reactor. The controller also maintains a desired excess oxygen concentration in the reactor effluent to ensure the complete destruction of the organic carbon compounds in the hydrolysate.

FA13-5 (I) 2951
Implementation of a predictive modeling technique on a DCS
Rietz, Christy A. — Iowa State Univ.
Rollins, Derrick — Iowa State Univ.

The implementation of a semi-empirical predictive modeling technique is demonstrated on a level controlled process operated by a distributed control system (DCS). This paper demonstrates the ability of this technique to accurately predict the response of the system with multiple changes in the input variable under a variety of sampling frequencies of the output variable. The new technique was implemented via a function sequence table as part of the configuration software of the DCS. In order for the technique to work, it is necessary to distinguish changes in the input variables over a small sampling interval from measurement noise. Our solution to the problem was analysis and quantification of the noise by use of a threshold to distinguish between real changes and signal noise.

FA13-6 (I) *
Panel Discussion

FA14-1 (I) 2956
Application of the Steiglitz-McBride identification algorithm to measured data from a power system simulator
Okamoto, H. — Tokyo Elect. Power Co.
Sanchez-Gasca, J. J. — GE Power Systems
Clark, K. — GE Power Systems
Wegner, C. A. — GE Power Systems
Miller, N. W. — GE Power Systems
Chow, Joe H. — Rensselaer Polytechnic Inst.

This paper demonstrates the application of the Steiglitz-McBride algorithm to the identification of low-order linear models using time domain measured data from a power system simulator. It is shown that the identified models retain the essential dynamic characteristics of the actual system, and are suitable for modal analysis and control of low frequency electromechanical oscillations.

FA14-2 (I) 2963
Multi-loop power system stabilizers using wide-area synchronous phasor measurements
Kamwa, Innocent — IREQ
Gerin-Lajoie, L. — Hydro-Quebec
Trudel, G. — Hydro-Quebec

A new distributed-measurement technology using the global positioning system and accurate phasor measurements units has developed steadily in recent years to become the most powerful source of wide-area dynamic information in a foreseeable future. This paper explores new ways of putting this extended real-time knowledge of the power system behavior into use, by means of supplementary feedback loops which improve dynamic and transient system stability and, ultimately, increase the existing transmission capacity. The design of such advanced controllers is based on a two-stage methodology of which first step is built on a powerful pulse-response-based, numerical subspace state-space identification algorithm to identify a reduced-order, small-signal MIMO model of the open-loop system. The second step is to select an appropriate control structure and then tune the stabilizer parameters accordingly. To tackle the most difficult situations, the architecture selected comprises several dynamic feedback loops, each consisting of a high-order differential filter. Controller tuning is then performed by minimizing a selective modal performance index in the parameter space. Adding stability and robustness constraints greatly improves the engineering significance of the resulting design. For illustration, we provide a full design of a three-loop stabilizer for a major synchronous-condenser station an actual power system which simultaneously uses two global and one local input signals. Both linear and nonlinear simulation results clearly demonstrate the added value of wide-area information when properly included in power system stabilizer design.

FA14-3 (I) 2968

SIMO system identification from measured ringdowns

Trudnowski, Dan J. Montana Tech
Johnson, Jeffrey M. Pacific Northwest National Lab.
Hauer, John F. Pacific Northwest National Lab.

Recent variations of Prony analysis and similar methods have proven to be valuable tools in identifying transfer functions and estimating the modal content from measured ringdowns. Such tools are becoming a standard in power system dynamic analysis. Current analysis methods assume the system to be single-input single-output (SISO) with distinct eigenvalues. Individual signals are analyzed independently often resulting in conflicting frequency and damping estimates (due to noise effects). Also, one cannot apply Prony analysis to systems with repeated or very closely-spaced poles such as in power system subsynchronous resonance problems. This paper presents a variation of Prony analysis that allows identification of a single-input multi-output (SIMO) proper model with possible repeated poles. Prony analysis as a signal analysis method is first generalized to handle multiple signals with poles that may be repeated. Expressions are then derived for the transfer function terms assuming the input is a series of square-wave pulses. Advantages of the SIMO analysis method are demonstrated on power system Monte Carlo type simulation model. The example shows that the SIMO formulation allows for more accurate estimation of electromechanical oscillation modes under noisy conditions (such as field measured data).

FA14-4 (I) 2973

Modeling of nonlinear system uncertainties using a linear fractional transformation approach

Boukarim, George ABB Power T&D Co.
Chow, Joe H. Rensselaer Polytechnic Inst.

This paper proposes a technique to model uncertain nonlinear systems whose models vary due to changes in the system configuration and operating conditions. To represent these variations in linearized models, the system state-matrices are expressed as matrix polynomials in the uncertain parameters. The representation of matrix polynomials in the form of a linear fractional transformation (LFT) is discussed, and algorithms based on controllability and observability conditions and singular value decomposition are proposed to reduce the order of the LFT form. The reduced LFT form of the state-matrices are then used in the state-equations to obtain a system model in the standard form. A power system model is used to illustrate this uncertainty modeling approach.

FA14-5 (I) 2980

Identifying swing mode bifurcations and associated limits on available transfer capability

DeMarco, Christopher L. Univ. of Wisconsin-Madison

Analytic techniques for predicting onset of voltage collapse in power systems often rely upon identification of a saddle node bifurcation. While many authors acknowledge that the separation between voltage phenomena and phase angle phenomena is far from absolute, most recent works have viewed voltage variation as the more significant problem. The goal of the work presented here is to shift focus back to loss of stability mechanisms associated with phase angle behavior and electromechanical swing modes. We will exploit structural features in the network to identify a typical form for the eigenvector associated with a bifurcating "swing mode" that reduces in frequency and ultimately looses stability. In a simple case study, we demonstrate that the participation of angles in such a mode is greater than that of voltages.

FA14-6 (I) 2986

Information, reliability, and control in the new power system

Hauer, John F. Pacific Northwest National Lab.
Taylor, C. W. Bonneville Power Administration

Deregulation of North American markets in electrical power promise serious new challenges to automatic control and to the information infrastructure in which automatic control is imbedded. What kind of control is viable under deregulation? The economic consequences of controller performance promise to be very high. Will infrastructure costs and liability issues discourage use of wide area controls? Can controller performance be assured to the extent that controller services can be marketed in the same sense as other commodities? In the quest for power system reliability, what new balance is evolving between automatic control and less technical methods? The intent of this paper is to further the dialog between the power system and the automatic control communities on such issues. Examples taken from the Western System breakups of 1996 argue that full use of automatic control as a means for power system reinforcement is strongly contingent upon new infrastructure for planning and operation.

FA15-1 2992

Fault tolerant strip tension control

Hearns, Gerald Univ. of Strathclyde
Grimble, Michael John Univ. of Strathclyde

A multivariable regulator for a hot strip mill is designed which is tolerant to a failure of the strip tension measurement. The reliable controller is obtained using a robust stability criterion with H-infinity controller synthesis. As well as ensuring that the system remains stable when the measurement is lost a bound can also be put on the drop in performance.

FA15-2 2997

Paper machine dry line position control during grade changes

Larsson, John Erik Lulea Univ. of Tech.
Gustafsson, Thomas Lulea Univ. of Tech.

The detection and control of the dry line machine direction position on a fourdrinier paper machine are considered in this work. The dry line position is detected using a digital image processing system consisting of a CCD camera, a frame grabber and a standard PC. The system was installed on a kraft liner machine and both open loop and closed loop experiments were performed with encouraging results. The introduction of automatic control of the dry line position reduces the time for grade changes and it also reduces the machine operators work load. The reduced time leads to smaller production losses and hence to economical benefits.

FA15-3 3002

Robust GMV cross directional control of paper machines

Stewart, Greg Honeywell-Measurex Devron Inc.
Gorinevsky, Dimitry M. Honeywell-Measurex Devron Inc.
Dumont, Guy A. Univ. of British Columbia

This paper considers the cross directional (CD) control of web manufacturing processes, such as in paper machines. In particular, it proposes a practical method for regularizing control of poorly controllable modes of the CD profile, while preserving the attenuation of the disturbances for the well controllable modes. A multivariable generalized minimum variance (GMV) controller is introduced. The GMV penalties are chosen so that the controller is robust to model identification errors and satisfies constraints on the size of the control action. The resulting feedback controller is an extension of the well-known Dahlin regulator. This controller has a familiar form including an actuator profile smoothing term, which is encountered in many industrial CD control systems, but was not analyzed in prior theoretical papers on the subject. The proposed design procedure is illustrated by designing a controller using data from a real paper machine.

FA15-4 3008

The virtual shaft control algorithm for synchronized motion control

Payette, Kevin HiTech Control Systems Inc.

This paper describes a control topology referred to as the Virtual Shaft, or Relative Stiffness, topology which is useful for synchronizing motion between multiple axes. Using simulation, the performance of the Virtual Shaft algorithm is compared to the standard called the Synchronized Master Reference algorithm. A 4-

axis web handling machine was chosen for the simulation, although the new algorithm can be used in servo applications, too.

FA15-5 3013
A cutting force monitoring system based on AC spindle drive

Huh, Kunsoo — Hanyang Univ.
Jung, Jung-Ju — Samsung Electronics Co.
Lee, Kang-Kyu — LG Electronics Co.

Monitoring of the cutting force signals in cutting process has been well emphasized in machine tool communities. Although the cutting force can be directly measured by a tool dynamometer, this method is not always feasible because of high cost and limitations in setup. In this paper an indirect cutting force monitoring system is developed so that the cutting force in turning process is estimated based on a AC spindle drive model. This monitoring system considers the cutting force as a disturbance input to the spindle drive and estimates the cutting force based on the inverse dynamic model. The inverse dynamic model represents the dynamic relation between the cutting force, the motor torque and the motor power. The proposed monitoring system is realized on a CNC lathe and its estimation performance is evaluated experimentally.

FA15-6 3018
Some observations on modeling and control of cement grinding circuits

Boulvin, M. — Poly. de Mons
Vande Wouwer, Alain — Poly. de Mons
Renotte, C. — Poly. de Mons
Remy, M. — Poly. de Mons
Lepore, R. — S.A. Cimenteries CBR

Based on system analysis and experimental data, a dynamic model of a closed-loop cement grinding circuit, which consists of a mixed set of algebraic and partial differential equations, is developed and validated. The model equations are solved numerically using the method of lines and the resulting simulation program is used to gain some insight into the process dynamics and to design and compare control loops to achieve product specifications. The influence of the model nonlinearities, which are related to the dependency of the rates of breakage on the mill hold-up, is highlighted. In particular, this nonlinearity introduces a strong coupling between PI control loops using the fresh feed flow rate and the louver position of the classifier as manipulated variables. Several variations of this basic control scheme are thoroughly analyzed, and the necessity of an efficient mill flow rate control for the stability of the fineness control loop is demonstrated.

FA16-1 (I) 3023
Optimal strain gauge placement for an instrumented disk drive suspension

Banther, Michael — Carnegie Mellon Univ.
Huang, Yuhong — Carnegie Mellon Univ.
Messner, William C. — Carnegie Mellon Univ.

The magnetic disk drive industry exhibits a continuing technological trend of ever increasing storage capacity requiring track densities of 25,000 tracks per inch by early in the next century. Successful operation at these track densities will require an increase of between 2.5 and 9 times in the closed-loop bandwidth of the head positioning servo-system. Resonance modes in the suspension of hard disk drives limit the closed-loop bandwidth. The bandwidth of the servo can be increased by state feedback of the vibration modes for active vibration control. This paper considers the optimal placement of strain gauge sensors on a suspension to observe the vibration states of the suspension. Using a finite element simulation of an actual suspension, a state space model is identified for the two normal strain and the shear strain at each finite element. The state space model includes the dynamics of the three primary resonance modes. A numerical search algorithm is used to determine the sensor location and orientation which maximizes the minimum singular value of the observability grammian. Results suggest that use of an instrumented suspension is viable candidate method for improve disk drive servo performance.

FA16-2 (I) 3028
Closed-loop control of a microfabricated actuator for dual-stage hard disk drive servo systems

Horsley, David — Univ. of California at Berkeley
Hernandez, Daniel — Univ. of California at Berkeley
Horowitz, Roberto — Univ. of California at Berkeley
Packard, Andrew K. — Univ. of California at Berkeley
Pisano, Albert P. — Univ. of California at Berkeley

This paper examines a dual-stage actuation scheme for magnetic hard disk-drives. The secondary actuator in this dual-stage design is a microfabricated, electrostatic actuator which has been used to position a disk-drive slider over a 2.5 kHz closed-loop bandwidth. Actuation tests were performed using laser-doppler vibrometer measurements of slider displacement, and both phase-lead and proportional-derivative controllers were implemented. The experimental results verify that the device has excellent linearity, suggesting that the dual-stage control system may use an observer to estimate the actuator displacement, resulting in significantly reduced implementation complexity. To this end, a SIMO dual-stage control system which uses only PES measurements is presented and compared to a MIMO control system which utilizes both the PES and measurements of the micro-actuator displacement.

FA16-3 (I) 3033
Multi-rate controller for hard disk drives with redesign of state estimator

Hara, Takeyori — Fujitsu Ltd.
Tomizuka, Masayoshi — Univ. of California at Berkeley

This paper describes a new multi-rate controller for Hard Disk Drives, which has a modified state estimator to correct estimated states not only at measurement instances of the position error signal but also at every control instance of updating the control input. This modification makes the control input smoother compared to the conventional multi-rate scheme. The effectiveness of the modified scheme is demonstrated by experiments.

FA16-4 (I) 3038
Multi-sensing servo with carriage acceleration feedback for magnetic disk drives

Kobayashi, Masahito — Hitachi, Ltd.
Yamaguchi, Takashi — Hitachi, Ltd.
Yoshida, Takashi — Hitachi, Ltd.
Hirai, Hiromu — Hitachi, Ltd.

A multi-sensing servo with a carriage-acceleration feedback to improve the sector servo in a magnetic disk drive has been designed. To increase a control bandwidth, the multi-sensing servo reduces the peak gain of a carriage mechanical-resonance, and there is no phase-lag up to near the control bandwidth. A carriage mechanical-resonance model is introduced that includes both the bending mode of a carriage arm and the elastic deformation mode of a pivot bearing. In place of a notch-filter circuit, the carriage-acceleration feedback controller has been implemented in an analog circuit. And experimental results show that the developed acceleration feedback controller is more effective for controlling head position than a usual sector-servo controller with a notch filter.

FA16-5 (I) 3043
Customizable coherent servo demodulation for disk drives

Abramovitch, Daniel Y. — Hewlett-Packard Labs

This paper describes the Customizable Coherent Demodulation Algorithm, a servo demodulator which provides dramatically improved performance over the currently used servo demodulation methods for disk drives. The demodulation algorithm proposed here makes better use of knowledge about the readback signal coming from the disk to provide better noise immunity and more immunity to other nonidealities in the magnetic head response. The net result is a demodulated Position Error Signal (PES) which has a much cleaner response.

FA16-6 (I) 3050

Servo performance prediction for high capacity disk drives

Lee, Ho-Seong — Maxtor Corp.
Guo, Lin — Maxtor Corp.

This paper proposes a simple yet effective way of building a simulation tool for predicting performance of disk drive servo systems for high TPI (tracks per inch) drives at early stage of their development. The simulation tool is built based on the identification of the plant model and mechanical disturbances of existing drives. It is a powerful tool for servo algorithm optimization and selection of critical parameters such as the sampling rate.

FM01-1 3055

Hybrid control for vibration and acoustics

Clark, Robert L. — Duke Univ.
Bernstein, Dennis S. — Univ. of Michigan

The “standard problem,” frequently discussed in the controls literature, is detailed for application to noise and vibration control. Specifically, the feedback, feedforward, and hybrid (combination of feedback and feedforward) control system architectures are developed in the framework of the standard problem. Methods of designing control systems for concurrent application of feedback and feedforward control are addressed, and the separability of the two control problems is demonstrated.

FM01-2 3060

Dynamic modelling of a smart material robot

Ge, S. S. — National Univ. of Singapore
Lee, T. H. — National Univ. of Singapore
Gong, J. Q. — National Univ. of Singapore

Three dynamic models of a smart material robot are presented in this paper. Firstly, Hamilton's approach is used to derive an accurate model described by partial differential equations (PDEs), which is not suitable for controller design. Based on the PDEs model, the Assumed Modes Method (AMM) and the Finite Element Method (FEM) are employed to derive two finite dimensional models in the forms of ordinary differential equations (ODEs) which are readily usable for the controller design. All of the models show that a smart material robot cannot be simply taken the same as that of a pure flexible robot. Comparative studies between AMM model and FEM model are carried out in both time and frequency domains to analyze the performance of the system and verify the correctness of the models.

FM01-3 3065

Model-free controllers of a single-link smart material robot

Gong, J. Q. — National Univ. of Singapore
Ge, S. S. — National Univ. of Singapore
Lee, T. H. — National Univ. of Singapore

In this paper, controller design is investigated for a single-link smart material robot, which combines both the advantages of flexible robots and piezoelectric materials. To avoid any drawbacks resulting from model uncertainties and/or model truncations, a class of model-free controllers (MFCs) are proposed for the smart material robot system to achieve both tip regulation and residual vibration suppression. In contrast to traditional model-based methods, the controllers presented here are derived from the basic energy-work relationship, which is independent of the system dynamics. Furthermore, the controllers are easily implementable because all the signals can be chosen readily measurable. Simulations are carried out to show the effectiveness of the presented approach.

FM01-4 3070

Input shaping designs to account for uncertainty in both frequency and damping in flexible structures

Pao, Lucy Y. — Univ. of Colorado
Lau, Mark A. — Univ. of Colorado

In the modeling of flexible structures, there is generally uncertainty in both the frequencies and damping constants, and it is thus important that the control methods for such systems be robust to these uncertainties. Input shapers have been shown to yield good performance while being insensitive to modeling errors. Most previous input shaping studies, however, have addressed only frequency modeling errors and further do not take into account the distributions of the parameter variations. We extend a recently proposed input shaping method, that allows the ranges of system parameter values to be weighted according to the expected modeling errors, for designing shapers that accommodate both frequency and damping uncertainty.

FM01-5 3072

An analysis and comparison of frequency-domain and time-domain input shaping

Pao, Lucy Y. — Univ. of Colorado
Cutforth, Craig — Univ. of Colorado

The technique of input shaping has been successfully applied to the problem of maneuvering flexible structures without excessive residual vibration. With input shaping, non-negative impulse shapers are often desired because they can be used with any arbitrary (unshaped) commands and not cause actuator saturation (if these original unshaped commands do not cause actuator saturation). We outline conditions when non-negative amplitude shapers will result when using frequency-domain methods of input shaping, and we draw comparisons with time-domain input shaping in terms of shaper length (speed) and number of impulses (ease of implementation).

FM01-6 3075

Control of a tip-loaded flexible-link robot using shaped input command

Yang, H. — National Univ. of Singapore
Ang, Jr., M. H. — National Univ. of Singapore
Krishnan, Hariharan — National Univ. of Singapore

In many applications, a robot end-effector (the tip) is required to follow a prescribed trajectory. This task is not easy to achieve for a flexible-link robot because it is known that the transfer function from the joint torque input to the tip position output is nonminimum phase. Output redefinition has been proven to be an effective method to address this issue and various output functions have been proposed. Along this line of development, a new output function is suggested in this paper. We show that the zero-dynamics of a flexible-link robot is exponentially stable with the newly defined output function. Asymptotic tracking of step input, linear and second order polynomial trajectories are achieved using this new technique while the link vibrations are damped out significantly. The unique feature of this technique is that the poles of the zero-dynamics can be placed at any desired locations in the left half of the s-plane. This enables us to suppress undesirable vibration very well while the robot tip is tracking a prescribed tip trajectory.

FM02-1 3077

A multi-objective dynamic programming approach to constrained discrete-time optimal control

Driessen, Brian J. — Sandia National Labs.
Kwok, Kwan S. — Sandia National Labs.

This work presents a multi-objective differential dynamic programming approach to constrained discrete-time optimal control. In the backward sweep of the dynamic programming in the quadratic sub problem, the sub problem input at a stage or time step is solved for in terms of the sub problem state entering that stage so as to minimize the summed immediate and future cost subject to minimizing the summed immediate and future constraint violations, for all such entering states. The method differs from previous dynamic programming methods, which used penalty methods, in that the constraints of the sub problem, which may include terminal constraints and path constraints, are solved exactly if they are solvable; otherwise, their total violation is minimized. Again, the resulting solution of the sub problem is an input history that minimizes the quadratic cost function subject to being a minimizer of the total constraint violation. The expected quadratic convergence of the proposed algorithm is demonstrated on a numerical example.

FM02-2 3084

Discretization of nonlinear models using a modified Carleman linearization technique

Al-Tuwaim, M. S. Univ. of Florida
Crisalle, Oscar D. Univ. of Florida
Svoronos, Spyros A. Univ. of Florida

A modification of the Carleman linearization procedure is proposed for discretizing nonlinear dynamic models for digital control applications. Neglected terms of a truncated Taylor series are approximated as linear combinations of kept terms. The process involves a series of adjustable parameters which are determined via optimization. Integration of the resulting linear model over a sampling period yields an analytic discrete-time model. Excellent discrete models of low orders are obtained in a study involving the nonlinear model of an isothermal continuous stirred tank reactor. The technique displays improved accuracy over a standard Carleman approach of the same order.

FM02-3 3089

Exploiting structure in a projective algorithm for solving strict linear matrix inequalities

Ge, Yuzhen Butler Univ.
Watson, Layne T. Virginia Poly. Inst. & State Univ.
Collins, Jr., Emmanuel G. Florida A&M - Florida State

This paper focuses on exploiting structure in a Lyapunov-type linear matrix inequality when solving a strict feasibility problem or a semidefinite programming problem using projective methods. A projective algorithm by Nemirovskii and Gahinet is modified so that both time and space complexity can be reduced.

FM02-4 3091

Extended matrix pencils for the delta-operator Riccati equation

Erwin, R. Scott USAF Research Lab.
Bernstein, Dennis S. Univ. of Michigan

This paper introduces an extended matrix pencil problem associated with the solution of the delta-operator (difference-operator) algebraic Riccati equation. A systematic treatment of the differential, shift, and difference operator algebraic Riccati equations based on decompositions of invariant subspaces of associated matrices is presented, along with a review of the associated generalized eigenvalue problems. The paper then presents an extended matrix pencil problem for all three operators. A summary of the relevant numerical solution techniques are also presented for completeness.

FM02-5 3096

An integrated procedure for fixed-point control implementation

Sureshbabu, Natarajan Ford Research Lab.
Powell, Barry Ford Research Lab.
Dunn, M. T. Ford Research Lab.

This paper provides a detailed description of the steps involved in translating a continuous-time control design into fixed-point microcontroller code.

FM02-6 3101

Computation of optimal feedback gains for time-varying LQ optimal control

Jaddu, Hussein Japan Adv. Inst. of Sci. & Tech.
Shimemura, Etsujiro Japan Adv. Inst. of Sci. & Tech.

A computational method is proposed to compute the optimal feedback control law of time-varying linear quadratic optimal control problem. The idea of the method is to use Chebyshev polynomials of the first type and their differentiation operational matrix to solve the matrix Riccati equation. To show the effectiveness of the proposed method, the simulation result of an example is shown.

FM03-1 3103

Maximizing tolerable disturbances in a coupled structural system using a QFT like method

Rhodes II, Q. Zane Texas A&M Univ.
Jayasuriya, Suhada Texas A&M Univ.

Considered in this paper is the real problem of controlling near field and far field acoustic signatures resulting from structural vibrations of a submarine hull. A simplified model for studying the acoustic signature consists of two beams connected by discrete elastic elements. A disturbance force W(s) acts on beam A, and a control force U(s) acts on beam B. This situation arises when a disturbance propagates through a coupled structure. A procedure for developing a controller to reject disturbances while satisfying constraints on the magnitudes of the input and output is presented. This was accomplished by mapping these constraints into equivalent bounds in the amplitude-phase plane. These bounds then serve as constraints during a loop shaping phase that characterizes the controller. Also, for a given closed loop system the maximum tolerable disturbance is identified. The method used is similar to the procedure outlined by Jayasuriya (1992), and the mathematical model for the coupled beam system is developed using component mode synthesis. Presented in this paper are the model development, generation of the design boundaries, controller design, and verification of the proposed isolation scheme.

FM03-2 3106

Decentralized state feedback stabilization and robust control of uncertain large scale systems with integrally constrained interconnections

Ugrinovskii, Valery A. Australian Defense Force Academy
Petersen, Ian R. Australian Defense Force Academy
Savkin, Andrey V. Univ. of Western Australia
Ugrinovskaya, E. Ya. Nizhny Novgorod Arch. & Civil Eng. Acad.

This paper is concerned with a problem of stabilization and robust control design for interconnected uncertain systems. The new class of uncertain large-scale systems is considered in which interconnections between subsystems as well as uncertainties in each subsystem are described by integral quadratic constraints. The problem is to design a set of local (decentralized) controllers which stabilize the overall system and guarantee robust disturbance attenuation in the presence of the uncertainty in interconnections between subsystems as well as in each subsystem. The paper presents necessary and sufficient conditions for the existence of such a controller. The proposed design is based on recent absolute stabilization and minimax optimal control results and employs solutions of a set of game-type Riccati algebraic equations arising in H-infinity control.

FM03-3 3111

Decentralized robust H-infinity control of uncertain large-scale systems with state-delays: LMI approach

Cheng, Chu-Wang China Textile Univ.
Tang, Bingyong China Textile Univ.
Cao, Yong-Yan Zhejiang Univ.
Sun, You-Xian Zhejiang Univ.

This paper deals with the problem of decentralized robust H-infinity control of uncertain systems with state delays. The parameter uncertainties are unknown but norm-bounded. The definition of decentralized robust H-infinity control of uncertain large-scale systems is proposed. A new sufficient condition is obtained for each subsystem and overall system to be stabilizable with given H-infinity norm bound via linear memoryless state feedback decentralized controllers. The results depend on the sizes of the delays and are given in terms of linear matrix inequalities. Finally, an illustrative example is presented.

FM03-4 3116

Robust decentralized stabilization for interconnected system with similar structure via output feedback

Chen, Bing Northeastern Univ.
Jing, Yuanwei Northeastern Univ.
Zhang, Si-Ying Northeastern Univ.

This note focuses on nonlinear uncertain interconnected systems with similar structures, and addresses the following robust

decentralized stabilizing problem: designing the decentralized static output feedback controller with similar structure such that the closed-loop system is asymptotically stable at its equilibrium point. It is shown that the similarity of interconnected systems can simplify the analysis and design of the systems.

FM03-5 3118
Toward linear complexity optimal control for sparsely interconnected dynamic systems
Driessen, Brian J. Sandia National Labs.
Sadegh, Nader Georgia Inst. of Tech.
Parker, Gordon G. Michigan Tech. Univ.

This work presents approaches aimed at achieving Order ((number of states)(number of time steps)) complexity for optimal control synthesis for sparsely interconnected dynamic systems. The methods are then applied to a concrete example of a mechanical rod discretized into a discrete number of masses connected with springs.

FM03-6 3121
Consultation scheme based on serial distributed detection system
Al-Ibrahim, M. M. Jordan Univ. of Science & Tech.
Al-Ababneh, N. K. Jordan Univ. of Science & Tech.

In this paper, we consider a serial distributed detection system of two sensors. Contrary to the known optimal serial decision fusion, we assume that two way conditional communication is allowed in serial fashion between the sensors. The performance of the proposed consulting scheme is shown to be identical to that of the optimal serial scheme when both systems operate at the same thresholds. It should be emphasized that the proposed consulting scheme exhibits the advantage of conditional nonrandom consultation between the sensors. Therefore, it has a higher survivability than that of the serial scheme. Performance results are given.

FM04-1 3124
Robust steady-state tracking for periodic systems
Zou, Liping Iowa State Univ.
Khammash, Mustafa H. Iowa State Univ.

In this paper, robust steady-state tracking of linear periodic systems is addressed in the presence of structured norm-bounded time-varying uncertainties. Robust steady-state tracking conditions are derived for sampled-data systems of known inputs and given as the spectral radius of certain nonnegative matrices. An approximate approach is developed and a computational algorithm is given to solve this problem.

FM04-2 3129
Robust controller synthesis for uncertain discrete-time periodic systems
Kapila, Vikram Polytechnic Univ.
Haddad, Wassim M. Georgia Inst. of Tech.

This paper addresses the problem of robust state feedback controller synthesis for discrete-time periodic systems with periodic parametric uncertainty. A stabilization technique for uncertain discrete-time periodic systems is developed which guarantees robust stability and performance in the face of system parametric uncertainty. The principal result of the paper involves a sufficient condition for characterizing robust full-state feedback periodic controllers for uncertain discrete-time periodic systems.

FM04-3 3131
Robust design of PID controllers including auto-tuning rules
Kristiansson, Birgitta Chalmers Univ. of Tech.
Lennartson, Bengt Chalmers Univ. of Tech.

A new method for fair evaluation of different controllers has recently been proposed. Low, high and mid-frequency properties are then treated separately in the evaluation of the closed loop performance and robustness. Experience from evaluation of parallel PID controllers has led to a set of simple rules for auto-tuning of stable non-oscillating processes. For this kind of plants serial PID controllers are also investigated, and it is shown that the best possible balance between low frequency performance and high frequency robustness is obtained by a double zero in the controller.

FM04-4 3133
Robust passification and control of non-passive systems
Kelkar, Atul G. Kansas State Univ.
Joshi, Suresh M. NASA Langley Research Ctr.

This paper addresses the use of passivity-based techniques to obtain robust controller design for non-passive uncertain systems. It extends the previous results on passivity-based control of non-passive systems to include robustness of passification in the presence of plant uncertainty. In particular, sufficient conditions for robust passification are obtained for different passification methods in the presence of various types of plant uncertainties. These conditions can be used either to check the robustness of a controller designed for a nominal plant model or to perform iterative controller design to meet certain robustness criteria. The plant uncertainty models used include additive, multiplicative, and feedback uncertainty. For each of these uncertainty models, conditions for robust passification are derived for three different passification methods, namely, series, feedback, and feedforward passification.

FM04-5 3138
Searching for robust minimal-order compensators
Stengel, Robert F. Princeton Univ.
Wang, Qian Princeton Univ.

A method of designing a family of robust compensators is presented. Each compensator's transfer function is found using a genetic-algorithm search for numerator and denominator coefficients that minimize the probability of unsatisfactory stability and performance, subject to uncertainty in the real parameters of the plant. As the search progresses, probabilities are estimated by Monte Carlo evaluation of stability and performance criteria. The design procedure employs a sweep from the lowest feasible transfer-function order to higher order, terminating either when design goals have been achieved or when no further improvement is evident. The study illustrates the evolution of pole and zero locations as compensator order increases for a benchmark problem in which settling-time and control-usage performance criteria must be satisfied subject to minimum likelihood of instability. The method provides a means for estimating the best possible compensation of a given order based on repeated searches.

FM04-6 3143
High performance state feedback, robust, and output feedback stabilizing control - a systematic design algorithm
Tsui, Chia-Chi

This paper improves a recent and fundamentally new design approach which can generally realize the robustness properties of the state feedback control for the first time, by guaranteeing the resulting feedback system stability. To the best of our knowledge, this improved design also provides the first simple and systematic design procedure and design solution to the strong stabilization problem -- stabilize feedback system by a stable output feedback compensator. Finally, high performance, high robustness and low controller order can all be systematically achieved by this design.

FM05-1 3148
An estimation-based approach to the design of adaptive IIR filters
Sayyarrodsari, Bijan Stanford Univ.
How, Jonathan P. Stanford Univ.
Hassibi, Babak Stanford Univ.
Carrier, Alain C. Lockheed Martin

We present an estimation-based approach to the design of adaptive IIR filters. We also use this approach to design adaptive filters when a feedback signal from the output of the adaptive filter contaminates the reference signal. We use an H-infinity criterion to cast the problem as a nonlinear H-infinity filtering problem, and present an approximate linear H-infinity filtering solution. This linear filtering

solution is then used to adapt the adaptive IIR Filter. The presentation of the proposed adaptive algorithm is done in the context of an adaptive Active Noise Cancellation (ANC) problem. Simulations are used to examine the performance of the proposed estimation-based adaptive algorithm.

FM05-2 3153
Worst-case estimation of unknown sinusoids contained in corrupted measurement data

Biswas, Saroj K. Temple Univ.
Subrahmanyam, M. Bala Naval Air Warfare Center

We present an H-infinity-type approach to the problem of estimation of sinusoids from noisy measurements. In this context, estimation of sinusoids means simultaneous estimation of frequencies, amplitudes, and phase angles of all sinusoidal components contained in the measured data. The estimation problem is formulated as a minimax optimization problem for minimization of estimation error in the presence of the worst-case noise of unknown statistics. The necessary conditions for the best sinusoids and the worst-case noise are derived. These conditions are given in terms of a nonlinear two-point-boundary-value problem which can be solved using numerical methods. Simulation results show a high estimation accuracy even in the presence of multiple sinusoids.

FM05-3 3158
Improved disturbance estimation for dynamic matrix control

Lee, Jay H. Auburn Univ.
Amirthalingam, Raja Auburn Univ.
Lee, Yongho Auburn Univ.
Lee, Kwang Soon Sogang Univ.

We propose a method to use historical data to improve disturbance estimation in Dynamic Matrix Control. It is proposed to compute the Kalman gain matrix of a step response model directly from plant data through a spectral or state-space realization. The Kalman filter can in turn be used to obtain an optimal prediction equation. The efficacy of the method is tested using a simulated heavy oil fractionator.

FM05-4 3163
Robust PFI Kalman filters

Linder, Stephen Paul Northeastern Univ.
Shafai, Bahram Northeastern Univ.

The Proportional Fading-Integral (PFI) Kalman filter is a generalization of the Proportional-Integral (PI) Kalman Filter. We show that integral action allows for the accurate estimate of disturbances caused by plant perturbations, dramatically improving the rejection properties of the Kalman filter. The fading integral of the PFI Kalman filter further extends the robustness of the filter by increasing the filter's stability margin, while allowing the rejection of transitory disturbances with unknown distribution matrices. Through extensive simulations, as applied to the 1992 ACC Robust Control Benchmark, we show that the fading integral doubles the stability margin of a Kalman filter-based state feedback regulator when used to estimate the rank one perturbation caused by a mismatched spring constant.

FM05-5 3165
Multi-rate nonlinear state estimation in a polymerization reactor

Tatiraju, Srinivas Drexel Univ.
Soroush, Masoud Drexel Univ.
Ogunnaike, B. E.I. du Pont de Nemours and Co.

A new multi-rate nonlinear observer design method is presented. It can use directly a nonlinear process model in the estimator design, without any linear approximation. The multi-rate nonlinear state observer is easy to design and implement and is computationally efficient. The implementation and performance of the observer design method are shown by a polymerization reactor in which free-radical solution polymerization of styrene takes place. The initiator concentration and the three leading moments of the molecular weight distribution (MWD) of the polymer product are estimated continuously from (i) the frequent measurements of the reactor temperature, jacket temperature and the reacting-mixture density and (ii) the infrequent and delayed measurements of the leading moments of the MWD obtained by a gel permeation chromatograph.

FM05-6 3170
Structural analysis and partitioning of dynamic process models for parallel state estimation

Abdel-Jabbar, Nabil Univ. of Michigan
Kravaris, Costas Univ. of Michigan
Carnahan, Brice Univ. of Michigan

This paper presents a new decomposition algorithm that attempts to partition a large dynamic system into loosely coupled subsystems to be solved concurrently on network-based parallel computers (multicomputers) for the purpose of state estimation. This new technique is based on structural properties of the dynamic system and parallel computing considerations. In particular, the rate of convergence of a dynamic iterative solution scheme, employed for the coordination of subsystem integrations on different computer nodes, is used as a criterion for the selection of the best system partitioning among candidate partitions.

FM06-1 3177
On closed-loop identification with a tailor-made parametrization

De Bruyne, Franky Australian National Univ.
Anderson, Brian D. O. Australian National Univ.
Gevers, Michel Univ. Catholique de Louvain
Linard, Natasha Australian National Univ.

In this paper, we present gradient expressions for a closed-loop parametric identification scheme. The method is based on the minimization of a standard identification criterion and a parametrization that is tailored to the closed-loop configuration. It is shown that for both linear and nonlinear plants and controllers, the gradient signals can be computed exactly.

FM06-2 3182
RBFN identification of a solution copolymerization model

Bomberger, John D. Univ. of California at Santa Barbara
Seborg, Dale E. Univ. of California at Santa Barbara
Ogunnaike, B. E.I. du Pont de Nemours and Co.

Methods developed for radial basis function network (RBFN) identification are applied to a complex multiple-input, multiple-output (MIMO) simulation. For RBFN identification, stepwise regression analysis is used, together with model order determination using the method of false nearest neighbors and width parameter estimation using approximate gradient norms. Industrially practical input sequence design is also considered.

FM06-3 3189
Minmax and least squares multivariable transfer function curve fitting: error criteria, algorithms and comparisons

Bohn, Christian Ruhr-Univ. of Bochum
Unbehauen, H. Ruhr-Univ. of Bochum

Two types of algorithms for minmax frequency response curve fitting for multivariable systems in matrix fraction description are discussed for different absolute error criteria. The first algorithm is a generalization of the well-known SK iteration, whereas the second algorithm is based on solving a sequence of reweighted nonlinear least squares problems. The error criteria treated are the maximum spectral norm of the error, the maximum infinity norm of the error, and the maximum infinity norm taken over the real and imaginary parts of the error. The performance of the algorithms is illustrated on simulated experimental data.

FM06-4 3194
Resampling-based calculation of the information matrix for general identification problems

Spall, James C. Johns Hopkins Univ.

The asymptotic normality of maximum likelihood and other general estimation schemes provide a powerful method for determining

statistical uncertainty bounds for the resulting estimates. This asymptotic normality result depends critically on the inverse Fisher information matrix as an approximation to the covariance matrix. Unfortunately, the Fisher information matrix is difficult to obtain in a large fraction of practical problems. This paper presents a relatively simple method for computing the Fisher information matrix based on a combination of Hessian matrix estimation and a computer-based resampling technique for averaging the Hessians. The Hessian estimation can be performed using either loss function values alone or, if available, values for the gradient of the loss function. The approach is demonstrated on a mid-sized estimation problem.

FM06-5 3199
Closed loop relevant identification of input-output and noise dynamics
De Bruyne, Franky Australian National Univ.

In this paper, we present a new closed-loop parametric identification setup that allows the estimation of both the input-output and noise dynamics. The method is based on the minimization of a standard identification criterion and a parametrization that is tailored to the closed-loop configuration.

FM06-6 3204
Identification of the smallest unfalsified model set based on stochastic noisy data
Fukushima, Hiroaki Kyoto Univ.
Sugie, Toshiharu Kyoto Univ.

In this paper, we propose a new model set identification method using experimental data contaminated by stochastic noise. We find the smallest model set which is consistent with the experimental data by separating the output error into the deterministic part due to the unmodeled dynamics and the stochastic noise part. Furthermore, the effectiveness of this method is shown by numerical examples.

FM07-1 3206
An extension of the generalized Hermite-Biehler theorem: relaxation of earlier assumptions
Ho, Ming-Tzu Texas A&M Univ.
Datta, Aniruddha Texas A&M Univ.
Bhattacharyya, Shankar P. Texas A&M Univ.

Recently in our earlier works, a generalization of the classical Hermite-Biehler Theorem was derived and shown to be useful for solving a number of fixed order and structure stabilization problems. This generalization, though adequate for solving these stabilization problems, required the assumption that the polynomial in question have no roots on the imaginary axis except for possibly a simple root at the origin. In this note, the result of our earlier works is extended to also allow roots on the imaginary axis: the main conclusion is that the roots, if any, at the origin modify the earlier Theorem statement only very slightly while the other imaginary axis roots leave it unchanged. The extension presented here permits a clearer exposition of the stabilization results in our earlier works.

FM07-2 3210
Notions of integral input-to-state stability
Sontag, Eduardo D. Rutgers Univ.

The input to state stability (ISS) property is a nonlinear version of stability with respect to the uniform norm. This paper introduces two variations of the ISS concept, to allow consideration of integrals when measuring the magnitude of an input or of a state trajectory. It is proved that one of the two properties is strictly weaker than ISS and the other one is equivalent to ISS.

FM07-3 3215
On impulse and continuous observation control design in Kalman filtering problem
Basin, Michael V. Auto. Univ. of Nuevo Leon
Pinsky, Mark A. Univ. of Nevada at Reno

This paper develops the observation control method for refining the Kalman-Bucy estimates, which is based on impulsive modeling of the transition matrix in an observation equation, thus engaging discrete-continuous observations. The impulse observation control generates on-line computable jumps of the estimate variance from its current position towards zero and, as a result, enables one to instantaneously obtain the estimate, whose variance is closer to zero. The filtering equations over impulse-controlled observations are obtained in the Kalman-Bucy filtering problem. The method for feedback design of control of the estimate variance is developed. First, the pure impulse control is used, and, next, the combination of the impulse and continuous control components is employed. The considered examples allow one to compare the properties of these control and filtering methodologies.

FM07-4 3220
Bilinear system control with exponential stability
Chen, Min-Shin National Taiwan Univ.

For a bilinear system that is open-loop neutrally stable, a quadratic state feedback control has been proposed to ensure global asymptotic stability of the closed-loop system. In this paper, a new nonlinear control is proposed so that the closed-loop system is not only globally stable but also exponentially stable. The new control results in a much faster state convergence rate; furthermore, it can be applied to a constrained bilinear system which is subject to whatever tight saturation limits on the control input.

FM07-5 3224
Asymptotic stability of completely retarded time-varying linear systems
Deng, Fei-Qi South China Univ. of Tech.
Liu, Yongqing South China Univ. of Tech.
Feng, Zhaoshu South China Univ. of Tech.

In this paper, asymptotic stability of completely retarded time-invariant linear systems is investigated with the Lyapunov functional method. Some delay inequalities is first established as lemmas, then a new type stability theorem is established for general retarded functional differential equations (RFDEs) and a sufficient criterion for the asymptotic stability of completely retarded time-varying linear systems is obtained, some corollaries on the asymptotic stability of zero solutions of completely retarded time-invariant linear systems are then given in algebraic form.

FM07-6 3226
Circle/Popov criteria in phaselock loop design
Wu, N. Eva Binghamton Univ.

Phaselock loops are generally designed by a combination of linear techniques, phase plane plots, rule of thumb, and simulation. It was only rather recently that Lyapunov's second method was formally applied to the design of phaselock loops. The method however, is not suitable for phaselock loops with high order filters. This note is intended to call the attention to the use of circle/Popov criteria for the design of phaselock loops, which has been made possible by the available power for numerical computation.

FM08-1 3229
H2 control with time domain constraints
Sznaier, Mario Pennsylvania State Univ.
Amishima, Takeshi Pennsylvania State Univ.

In this paper we study the problem of minimizing the H2 norm of a given transfer function subject to time-domain constraints on the time response of a different transfer function to a given test signal. The main result of the paper shows that this problem admits a minimizing solution in H2. Moreover, rational solutions with performance arbitrarily close to optimal can be found by constructing a family of approximating problems. Each one of these problems entails solving a finite-dimensional quadratic programming problem whose dimension can be determined before hand.

FM08-2 3234

Performance limitations for unstable SISO plants

Havre, Kjetil — Norwegian Univ. of Science & Tech.
Skogestad, Sigurd — Norwegian Univ. of Science & Tech.

This paper examines the fundamental limitations imposed by instability in the plant (Right Half Plane (RHP) poles) on closed-loop performance. The main limitation is that instability requires active use of plant inputs, and we quantify this in terms of tight lower bounds on the input magnitudes required for disturbance and measurement noise rejection. These new bounds involve the H-infinity norm, which has direct engineering significance. The output performance in terms of disturbance rejection or reference tracking is only limited if the plant has RHP-zeros. It is important to stress that the derived bounds are controller independent and that they are tight, meaning that there exists controllers which achieve the lower bounds.

FM08-3 3239

Design of optimal mixed H2/H-infinity static state feedback controllers

Halder, Bijit — Stanford Univ.
Hassibi, Babak — Stanford Univ.
Kailath, Thomas — Stanford Univ.

Despite the recent advances in robust control theory, the robust performance problem formulated in the mixed H2/H-infinity framework largely remains an open problem. In this approach, one seeks a controller that minimizes the H2 norm of a closed-loop map over all admissible controllers while satisfying an H-infinity constraint on another closed-loop map. Unlike the optimal H2 problem or the gamma-level sub-optimal H-infinity problem, the mixed H2/H-infinity problem does not have a readily computable solution. In this paper we restrict consideration to static state feedback controllers and propose an efficient iterative algorithm for computing the optimal H2/H-infinity solution.

FM08-4 3244

Multiobjective H2/H-infinity optimal control via finite dimensional Q-parametrization and linear matrix inequalities

Hindi, Haitham — Stanford Univ.
Hassibi, Babak — Stanford Univ.
Boyd, Stephen P. — Stanford Univ.

The problem of multiobjective H2/H-infinity optimal controller design is reviewed. There is as yet no exact solution to this problem. We present a method based on that proposed by Scherer. The problem is formulated as a convex semidefinite program (SDP) using the LMI formulation of the H2 and H-infinity norms. Suboptimal solutions are computed using finite dimensional Q-parametrization. The objective value of the suboptimal Q's converges to the true optimum as the dimension of Q is increased. State space representations are presented which are the analog of those given by Khargonekar and Rotea for the H2 case. A simple example computed using FIR (Finite Impulse Response) Q's is presented.

FM08-5 3250

Multiobjective L1/H-infinity controller design for systems with frequency and time domain constraints

Haddad, Wassim M. — Georgia Inst. of Tech.
Chellaboina, Vijaya S. — Georgia Inst. of Tech.
Kumar, Rohit — Stanford Univ.

In this paper we develop an optimal mixed-norm L1 bound/H-infinity controller synthesis framework for continuous-time linear systems. This multiobjective problem is treated by forming a convex combination of both L1 (time domain worst-case peak amplitude response) and entropy (frequency domain worst-case H-infinity disturbance attenuation) performance measures. For flexibility in controller synthesis, we adopt the approach of fixed-structure controller design which allows consideration of arbitrary controller structures, including order, internal structure, and decentralization. Finally, using a quasi-Newton continuation algorithm, we demonstrate the effectiveness of the proposed mixed-norm L1/H-infinity approach via a numerical design example.

FM08-6 3255

Fixed-order dynamic compensation for linear systems with actuator amplitude and rate saturation constraints

Chellaboina, Vijaya S. — Georgia Inst. of Tech.
Haddad, Wassim M. — Georgia Inst. of Tech.

In this paper we develop fixed-order (i.e., full- and reduced-order) controllers for linear systems with actuator amplitude and rate saturation constraints. The problem is formulated as a multiobjective problem involving a convex combination of an L1 norm and the H2 norm to capture actuator saturation constraints and closed-loop system performance in the face of exogenous white noise disturbances. The L1 convolution operator norm considered is induced by bounded amplitude persistent L-infinity disturbances and L-infinity performance variables involving the actuator amplitude and rate signals. Hence, the peak pointwise-in-time actuator amplitude and actuator rate excursion is guaranteed to be less than the product of the L1 convolution operator norm and the L-infinity disturbance amplitude bound. Application of the proposed framework to the design of multivariable saturation controllers for the control of a bank-to-turn missile is demonstrated.

FM09-1 3261

Model predictive control for uncertain systems

Chai, Li — Zhejiang Univ.
Sun, You-Xian — Zhejiang Univ.
Cao, Yong-Yan — Univ. of Hong Kong

A new model predictive control (MPC) algorithm for uncertain system is presented. This approach is less conservative than "robust MPC" and is equivalent to standard model algorithm control (MAC) in the case of the certain system. A useful simplified algorithm being more acceptable to industrial process is also given. The advantage of the new algorithm is illustrated by two examples.

FM09-2 3266

Frequency domain robust control design with predictive control action

Grimble, Michael John — Univ. of Strathclyde

A generalized predictive H-infinity control law is derived in the frequency domain which closely follows the usual polynomial solution of the H-infinity problem. A constraint is applied that both the control and future predicted controls are calculated using the same time-invariant control algorithm.

FM09-3 3271

Global predictive stabilization of input-saturated linear systems

Casavola, Alessandro — Univ. of Florence
Giannelli, Monica — Univ. of Florence
Mosca, Edoardo — Univ. of Florence

A predictive regulator is described for stabilizing linear plants subject to input-saturation constraints. While, asymptotic stability of general linear plants is ensured subject to a set-membership condition on the initial state, global exponential regulation is achieved in the presence of input saturations for plants which are asymptotically null-controllable with bounded inputs. The design knobs of the regulator can be chosen off-line so as to trade off between non-conservative regulation performance vs. computational complexity.

FM09-4 3276

On receding horizon extensions and control Lyapunov functions

Primbs, James A. — California Inst. of Tech.
Nevistic, Vesna — ETH Swiss Fed. Inst. of Tech.
Doyle, John C. — California Inst. of Tech.

Control Lyapunov functions (CLFs) are used in conjunction with receding horizon control (RHC) to develop a new class of control schemes. In the process, strong connections between the seemingly disparate approaches are revealed, leading to a unified picture that ties together the notions of pointwise min-norm, receding horizon, and optimal control. This framework is used to develop a control Lyapunov function based receding horizon scheme, of which a

special case provides an appropriate extension of a variation on Sontag's formula. These schemes are shown to possess a number of desirable theoretical and implementation properties. An example is provided, demonstrating their application to a nonlinear control problem.

FM09-5 3281

A computationally efficient constrained predictive control law

Rossiter, J. Anthony — Loughborough Univ.
Rice, M. J. — Loughborough Univ.
Schuurmans, J. — Loughborough Univ.
Kouvaritakis, Basil — Oxford Univ.

A predictive control algorithm is presented that uses a weighted sum of Linear Quadratic (LQ) optimal predictions and 'Mean Level' predictions. Each time step only a single weighting parameter is solved for using a Linear Program problem hence giving a low computational load. The controller achieves LQ-optimality when constraints are inactive, and remains feasible (under mild conditions) if constraints are active.

FM09-6 3286

Predictive and time delay control of transmission mechanisms

Chen, Cheng-Yi — National Sun Yat-Sen Univ.
Cheng, Chi-Cheng — National Sun Yat-Sen Univ.
Chiu, George T.-C. — Purdue Univ.

In this paper, a control strategy, which combines predictive control with zero phase error tracking controller (ZPETC) and time delay scheme, is developed to overcome positioning and tracking difficulties for transmission mechanism with friction. Time delay control is used to cancel disturbances and potential nonlinearities. Predictive control uses future and past information to maintain servo performance, regulator performance and robust stability under the influence of disturbance and measurement noise. ZPETC is included to improve the overall system bandwidth. A cycloidal velocity profile is used to generate smooth reference motion to avoid saturating the actuator. Realistic numerical simulations that considered the effect of sampling, quantization and friction were performed to investigate the effectiveness of the proposed control scheme. Encouraging transient response and steady-state control performance were observed in the results of positioning control simulation of a one-dimensional transmission mechanism.

FM10-1 3291

Fault detection and diagnosis for rotating machinery: a model-based approach

Abdel-Magied, M. F. — Case Western Reserve Univ.
Loparo, Kenneth — Case Western Reserve Univ.
Lin, Wei — Case Western Reserve Univ.

This work formulates the problem of incipient fault detection and diagnosis for rotating machinery in a statistical model-based framework. This includes problem description, modeling of rotating machinery and fault mechanisms, formulation of the detection and diagnosis problem, and analysis of performance of the proposed technique.

FM10-2 3297

Electric fault detection for vector-controlled induction motors using the discrete wavelet transform

Chen, Chao-Ming — Case Western Reserve Univ.
Loparo, Kenneth — Case Western Reserve Univ.

This paper focuses on the detection of electrical faults in vector-controlled induction motor systems. Systems controlled by a robust mechanism, such as vector control, have an increased ability to adapt to changes in system parameters and reject disturbances. Therefore, if there are faults in the system they may be difficult to detect. The controller tends to compensate for the faults and minimize their impact on the system outputs. A fault detection algorithm based on the Discrete Wavelet Transform is developed. The algorithm computes a "fault index" for stator winding faults such that fault signature and the fault degree can be determined in a clear manner.

FM10-3 3302

Fault detection for systems with multirate sampling

Fadali, Mohammed Sami — Univ. of Nevada
Liu, W. — Univ. of Nevada

In this paper, we consider multirate sampled-data systems with a single input sampling period and multiple output sampling periods that are integer multiples of the input sampling period. We modify the Chow-Willsky approach to obtain a residual generator design for this class of multirate systems. We derive conditions for the existence of residual generators that guarantees fault detection and disturbance rejection. We also derive conditions of the existence of a structured residual generator. An example is presented to illustrate our approach.

FM10-4 3307

Robust detection and isolation of mechanical faults in processes driven by induction machines

Zell, Caj — Lulea Univ. of Tech.
Medvedev, Alexander V. — Lulea Univ. of Tech.

A robust model-based technique for fault detection and isolation in electro-mechanical systems comprising induction machines is introduced. A state observer for reconstructing the magnetic flux components of the induction machine and thereby the electrical torque is used in combination with a robust state estimator for the mechanical load torque based on a model with structured uncertainties. The Fault Detection and Isolation problem is reduced to validation/invalidation of the models representing different fault hypothesis. The practical applicability of the method is demonstrated in a simulation example.

FM10-5 3312

The application of kernel density estimates to condition monitoring for process industries

Chen, Qian — Sheffield Hallam Univ.
Goulding, P. — Manchester Univ.
Sandoz, D. — Manchester Univ.
Wynne, Richard J. — Sheffield Hallam Univ.

This paper discusses the application of kernel extraction for estimating the non-parametric density function of a multivariate process system for condition monitoring purposes. In particular, this paper concentrates on a real industrial case study to demonstrate the differences and practical capability of three different estimators. It is shown that the kernel density estimate has the potential to be an important technique of obtaining real nonparametric empirical density function of the process population as an aid to more effective intelligent condition monitoring.

FM10-6 3317

Damage mitigating control of a reusable rocket engine for structural durability

Holmes, Michael Scott — Pennsylvania State Univ.
Patankar, Ravindra — Pennsylvania State Univ.
Ray, Asok — Pennsylvania State Univ.
Tangirala, Sekhar — Pennsylvania State Univ.

The goal of damage mitigating control is to achieve a desired level of trade-off between structural durability of critical component(s) and overall dynamic performance of the plant (e.g., aircraft, spacecraft, and energy conversion systems). This paper presents the synthesis of damage-mitigating output feedback controllers and applies this method to a reusable rocket engine by taking fatigue crack damage of turbine blades into consideration. The effects of crack growth retardation due to overload are included in the fatigue damage model which is formulated in the state-space setting. Simulation results are presented to demonstrate the effectiveness of the damage-mitigating control concept.

FM11-1 3322

Acceleration feedback of tracking control based on real time Fourier series

Tang, Xiaoqi — Hong Kong Univ. of Science & Tech.
Cai, Lilong — Hong Kong Univ. of Science & Tech.
Huang, Weiqing — Hong Kong Univ. of Science & Tech.

Acceleration feedback can be very useful in improving the performance of the closed-loop system, as indicated by many researchers. However, the difficulty in obtaining a good acceleration signal limits its applications. Acceleration estimation through numerical differentiation is noisy and direct measurement using an accelerometer may not be possible due to the cost or the availability. In this paper we propose a new method of estimating the acceleration signal using Real time Shifting Digital Fourier series (FS) Transformation (RSDFT) and use this estimated acceleration as a feedback signal. Since the acceleration obtained through RSDFT is expressed in FS with finite terms, the high frequency noise and the resonant frequency of the system can be easily removed from the feedback signals. Therefore, high gain can be used to improve the performance of the closed-loop system. An experiment on a positioning table shows that this new method is effective in tracking control both in performance and implementation.

FM11-2 3327

Linear discrete-event systems and robust servomechanism problem

Iftar, Altug — Anadolu Univ.

Linear discrete-event systems are studied. Reachability, observability, controllability, constructibility, stabilizability and detectability of such systems are investigated. Stability of linear discrete-event systems is also considered. It is shown that a stabilizable and detectable linear time-invariant discrete-event system can be stabilized by a linear time-invariant discrete-event controller. Robust servomechanism problem for linear discrete-event systems is also discussed. The necessary and sufficient conditions for the existence of a solution to this problem are presented.

FM11-3 3332

Improved tracking under zero preview information for SISO systems

Bement, Matt — Texas A&M Univ.
Jayasuriya, Suhada — Texas A&M Univ.

In this paper we consider the problem of continuous tracking of a reference signal assumed to be a linear combination of polynomials, exponentials and sinusoids of known frequencies. As in [1], the concept of orthogonality and the Diophantine equation are used to construct a prefilter with specified preview information. For the purposes of this paper, only the zero preview case is considered. We exploit the non-uniqueness of the Diophantine equation solution to construct a prefilter that is optimal in a certain sense.

FM11-4 3334

Comparison of suboptimal strategies for optimal own-ship maneuvers in bearings-only tracking

Logothetis, Andrew — Royal Inst. of Tech.
Isaksson, Alf — Royal Inst. of Tech.
Evans, Robin J. — Univ. of Melbourne

Suboptimal optimization techniques for computing observer trajectories in the bearings-only tracking problem, are considered. It is well known that the observer motion can aid in the quality of track performance. The aim is to obtain tight bounds on the location and velocity of this target through own ship maneuvers. In [Logothetis, Isaksson and Evans, CDC97], two mutual information measures were derived and optimal trajectories were computed via dynamic programming. The memory requirements and the computational burden for computing optimal observer paths via dynamic programming is prohibitive. Thus, suboptimal strategies are explored here which considerably reduce the computational cost. The optimization methods are divided into two groups. In the first group a scalar function of the target state error covariance matrix is minimized, while in the second group approximate forward - reduced complexity - dynamic programming techniques are used. Simulation studies are carried out that compare the suboptimal optimization methods proposed in this paper.

FM11-5 3339

Design of time delay controller based on variable reference model

Song, Jae-Bok — Korea Univ.
Byeon, Kyeong-Seok — Korea Univ.

Many plants have upper and lower bounds beyond which saturation of control efforts occurs. Since the saturation adversely affects control performance, it should be avoided if possible. In this paper a new approach of avoiding saturation by varying the reference model for TDC (time delay control) based systems subject to the step changes in reference inputs. In this scheme, the variable reference model is determined based on the information on control inputs and the size of the step changes in the reference inputs. This scheme is verified by application to the position control experiments using a brushless DC servo system.

FM11-6 *

Withdrawn

FM12-1 3344

State realization of nonlinear systems described by input-output difference equations

Sadegh, Nader — Georgia Inst. of Tech.

In this paper, we consider a general class of nonlinear discrete-time systems described by their input-output relationship. We first present the necessary and sufficient conditions for existence of a local observable state-space realization of the system and an explicit algorithm for computing it. In cases where the input-output map and its resulting realization are nonminimal, we formulate an algorithm for extracting its minimal realization whenever possible. The developed theory and algorithms are illustrated by means of several examples.

FM12-2 3349

Sufficient conditions for minimality of a nonlinear realization via controllability and observability functions

Scherpen, Jacquelien M. A. — Delft Univ. of Tech.
Gray, W. Steven — Old Dominion Univ.

In this paper we develop a set of sufficient conditions in terms of controllability and observability functions under which a given state space realization of a formal power series is minimal. Specifically, it will be shown that positivity of these functions, plus a few technical conditions, implies minimality. In doing so, connections are established between Hamilton-Jacobi type optimal control theory and the well known necessary and sufficient conditions for minimality in terms of Kalman type rank conditions on the accessibility and observability distributions.

FM12-3 3354

Simplification of nonlinear controllers: balancing approaches

Min, Hong — Drexel Univ.
Yousuff, Ajmal — Drexel Univ.

This paper extends works of linear controller reduction to nonlinear affine systems with the help of nonlinear balancing concept and technique. For stable controller, nonlinear model reduction is directly applied to reduce the order. Discussion for unstable controller reduction focuses on H-infinity suboptimal output feedback controller and other controllers with observer-based structures. An unstable controller is reconstructed based on its left (right) coprime factorization such that the above controller reduction technique can be applied. Stability of the closed-loop system with reduced controller is discussed and the upper bound of the closed-loop system performance with respect to L2-gain is also obtained.

FM12-4 3359

Robust stabilization of nonminimum phase nonlinear systems

Jo, Nam H. — Seoul National Univ.
Byun, Jijoon — Seoul National Univ.

Shim, H. Seoul National Univ.
Seo, Jin H. Seoul National Univ.

The problem of robust stabilization for nonlinear systems with mismatched uncertainties is further studied by extending the results of Liao (1992) to the case where nonlinear systems either fail to have well-defined relative degree or have unstable zero dynamics. The approach is based on the approximate input/output linearization introduced by Hauser (1992) and an appropriate transformation introduced by Allgower (1997) which transforms the given nonlinear system into a special normal form. The proposed feedback controller guarantees that all the states will remain bounded.

FM12-5 3364
The construction of the set of stable states for constrained systems with open-loop unstable plants
McNamee, Joe Air Force Inst. of Tech.
Pachter, Meir Air Force Inst. of Tech.

Control in the presence of hard control and state constraints, and open-loop unstable plants, is addressed. A methodology for the construction of a set of stable states of a tracking control system is presented. A saturation avoidance control strategy is employed, and the exogenous reference signal is modified nonlinearly so that the controlled process state is constrained to a positively invariant set. Stability is guaranteed for all initial states in this set. The said set is an arbitrarily close approximation to the maximal statically admissible set. Characterization of this set is an important stepping stone in the synthesis of tracking controllers.

FM12-6 3369
Stabilizing decomposition of interval nonlinear interconnected discrete control systems with nonintegral-delays
Zhang, Xinzheng South China Univ. of Tech.
Liu, Yongqing South China Univ. of Tech.

This paper gives a structural concept for interval nonlinear discrete control systems with nonintegral delays, on the basis of the comparison principle and the frequency equivalence method. A sufficient criteria is obtained for the interconnected robust stabilization of interval nonlinear interconnected discrete control systems with nonintegral-delays and perturbation parameters. At the same time, some estimate formulas of the bound for both time-delays and perturbation parameters are given.

FM13-1 (I) 3371
Optimization of molecular weight distribution using batch-to-batch adjustments
Clarke-Pringle, T. McMaster Univ.
MacGregor, J. F. McMaster Univ.

A batch-to-batch optimization methodology for producing a desired MWD using an approximate model is presented. A measurement of the MWD at the end of the batch is used to update manipulated variable trajectories for the next batch, thus iterating into a good operating policy. The optimization approach is then extended for use as an on-line control method. A multivariable statistical process control (MSPC) monitoring scheme is developed for deciding when a new batch optimization is required. The optimizer remains on, but dormant while the desired MWD is being produced, and re-optimizes the process quickly if the process changes and poor quality polymer is produced. The combined MSPC/batch-to-batch optimizer is demonstrated on a simulated semi-batch polystyrene reactor.

FM13-2 (I) 3376
Model-based control of injection pultrusion process
Voorakaranam, Srikanth Washington Univ.
Kardos, John L. Washington Univ.
Joseph, Babu Washington Univ.

In this paper, we address the quality control issues in manufacturing of fiber-resin composites through a prototype process called Injection Pultrusion (IP). The objective is to maximize production rates while maintaining quality. It is demonstrated that a parallel cascade control strategy which uses an online process model is suitable in meeting this objective. The strategy uses steady-state cure and pressure models, in conjunction with an optimizer. A first principles model is exercised to generate input data for the feature selection procedures. Based on statistical significance tests, streamlined regression models are generated by identifying processing variables and parameters having a crucial bearing on the part quality and eliminating superfluous variables. Infrequent quality measurements are used to correct for modeling errors. Closed loop control results are presented to demonstrate the successful working of the strategy.

FM13-3 (I) 3381
Nonlinear model predictive control of a batch polymerization process
Schei, Tor Steinar SINTEF Electronics & Cybernetics
Singstad, Peter SINTEF Electronics & Cybernetics

A Newton-type nonlinear model predictive control (NMPC) algorithm is applied through a simulation study to a batch reactor for polymerization of phenol-formaldehyde resole resins. The NMPC algorithm is combined with a recursive state and parameter estimation algorithm and a nonlinear state-space model, which is used both for the estimation and the prediction. The state-space process model is developed from first principles, and uncertain parameters are estimated off-line from logged process measurements. Some of the parameters can not be assumed to be constant during the batch, and should be estimated on-line during operation. NMPC strategies are compared with the conventional reactor control. The basic strategy is to maximize the reaction rate, with constraints on the reactor temperature and the heat of reaction. The latter constraint is determined by available cooling capacity. The simulation study indicates a potential reduction in batch cycle time of approximately 80 minutes, with safety margins at least as high as with conventional control and without increasing the maximum reactor temperature.

FM13-4 (I) *
Withdrawn

FM13-5 (I) 3386
Robust model predictive control of an industrial solid phase polymerizer
Krishnan, Arun Univ. of South Carolina
Kosanovich, Karlene A. Univ. of South Carolina
DeWitt, Marion R. Dupont Chemical Co.
Creech, Michael B. Dupont Chemical Co.

This study presents the application of model predictive control (MPC) to regulate a continuous solid phase polymerization reactor according to pre-specified, multi-objective criteria. MPC is the descriptive name given to a class of computer control schemes that utilize a process model for two central tasks: 1. Explicit prediction of future plant behavior and 2. Computation of appropriate corrective control action to drive the predicted output towards the desired target value. MPC is especially formulated to compensate for disturbances in multivariable systems and it is capable of handling systems that exhibit time delays, inverse response and other unusual process dynamics. Conventional MPC uses linear models of the process to predict the future outputs even when the process is nonlinear. The industrial example selected is a nylon solid phase polymerization reactor. Polymerization is an extremely complex process which is a function of operating conditions such as, temperature, humidity, pressure, etc. The solid phase polymerizer is a continuous reactor used for remelting and repolymerization of the solid polymer flake. The water content in the polymer, a critical process parameter, is maintained by circulating moist gas through the reactor. The controlled variable, the transfer line pressure drop, is used to infer the molecular weight distribution of the end product as it is not directly measured. The presence of multiple variables affecting the controlled variable necessitates the use of an intelligent control strategy to manipulate a number of variables simultaneously. PID algorithms, although effective, seldom lead to optimal utilization of resources and raw materials and hence the choice of implementing MPC as the control strategy. The paper discusses the implementation of one particular MPC strategy called Robust Model

Predictive Control Technology developed by Honeywell. The identification of the process models for the various controlled variable-manipulated variable pairs will be discussed and analyzed. The results obtained from on-line implementation of the controller will be presented.

FM13-6 (I) 3391

Artificial neural network feedforward/feedback control of a batch polymerization reactor

Shahrokhi, Mohammed — Sharif Univ. of Tech.
Pishvaie, Mahmoud Reza — Sharif Univ. of Tech.

Control of polymerization reactors is a challenging problem due to nonlinear behavior of most polymer reactions. When the reaction is carried out in a batch reactor, the problem becomes even more difficult. In this work, temperature control of a batch polymerization of methylmetacrylate (MMA) is considered. The mathematical model developed by Ross and Laurence for suspension polymerization of MMA is used for computer simulation and control. The heat generation term is considered as a load and estimated via a trained feedforward artificial neural network . A feedforward/feedback control algorithm is used for controlling the reactor and the performance of the proposed scheme is compared with well tuned PID controller. Simulation studies show that the neural network is able to estimate the heat of reaction very well and considerable improvement in the closed loop performance has been observed.

FM14-1 3396

Capacitor switching transients prediction in noisy environments

Sochuliakova, D. — Drexel Univ.
Niebur, Dagmar — Drexel Univ.
Nwankpa, Chika O. — Drexel Univ.
Fischl, Robert — Drexel Univ.
Richardson, D. — Electric Power Research Inst.

The purpose of this project is to design a voltage transient predictor capable of predicting voltage across the load N time steps into the future. The system is modeled as a generator bus and a load bus connected by a short line model with a switchable capacitor placed along the line. Based on the analytical expression for system states, a novel discrete Kalman filter model is proposed, and used for prediction. A study with respect to capacitor position, switching time, noise level, and number of predicted time steps was conducted.

FM14-2 3398

Subspace based identification of power transformer models from frequency response data

Akcay, Huseyin — Tubitak Marmara Research Centre
Islam, Syed M. — Curtin Univ. of Tech.
Ninness, Brett M. — Univ. of Newcastle

A recent frequency-domain, subspace-based algorithm is used in the identification of two power transformers. The results indicate that the subspace-based identification algorithms can be used without modification even when the dynamic range of frequency response data is large.

FM14-3 3403

A hybrid robust power system control design combining system identification and genetic algorithms

Tito, Flavia L. — Instituto Militar de Engenharia
Taranto, Glauco N. — Fed. Univ. Rio de Janeiro
Pellanda, Paulo C. — Instituto Militar de Engenharia

This paper presents a hybrid control design method that combines features from a system identification problem with meta-heuristics of Genetic Algorithms (GA). The main objective of the method is to find robust controllers that make the closed-loop system less sensitive to parametric uncertainties and also force the closed-loop spectrum to be located in a sub region that represents minimum damping. Minimum-phase low-order decentralized dynamic-output-feedback controller structure is readily accomplished in the proposed method. The approach is devised to be applied in the design of power system damping controllers. However, the mathematical treatment employed is general to other engineering applications.

FM14-4 3408

Nonlinear dynamics, control, and stability analysis of power systems

Lyshevski, Sergey — Purdue Univ. at Indianapolis
Yokomoto, Charles — Purdue Univ. at Indianapolis

This paper considers nonlinear analysis and design for highly nonlinear power systems. These nonlinear features are addressed in terms of the Lyapunov stability theory. The current trends in application of heavily loaded power systems motivate the use of a nonlinear framework to handle a large variety of nonlinear phenomena. To ensure a complete understanding of the power system dynamics, as well as to tackle nonlinear control problems, this paper offers an integrated perspective. In particular, analysis and design are performed by using nonlinear augmented models of power systems (generation system - transmission line - load). All aspects of nonlinear dynamics and controls are explored by applying the Lyapunov stability theory. By using the Lyapunov second method, new results are offered, and examples demonstrate the proposed analysis and design procedures.

FM14-5 3410

Dynamic optimal reactive power flow

Sharif, S. Salamat — Univ. of New Brunswick
Taylor, James H. — Univ. of New Brunswick

An efficient method for minimization of energy loss over intervals of time is presented. The proposed method uses different loading conditions during each given time interval instead of one single snapshot of the network. The given interval is divided into several shorter periods; the first load condition is a current snapshot and subsequent ones are forecasted. All controls are set optimally at the beginning of the interval, and then only the continuous controls are adjusted at the beginning of each subsequent period. This strategy avoids excessive adjustment of transformer tap settings and discrete var sources switching. By increasing the number of periods or load profiles, the dimension of problem will rise substantially. This problem is thus handled by using the Generalized Bender Decomposition technique. With this technique, the loading condition for each period will be solved in a separate nonlinear programming (NLP) subproblem. The results of the NLP subproblems will be coordinated in a master problem. As shown in simulation results, the proposed method not only decreases the total energy loss over the given interval, but it also improves the voltage profile.

FM14-6 3415

Partially decentralized controller for damping interarea oscillations in power systems

Silva de Araujo, Clivaldo — Univ. Federal da Paraiba
Calazans de Castro, Jose — Univ. Federal da Paraiba

Frequency Domain techniques for analysis and for design of controllers with remote feedback signals to damp out interarea oscillations in large-scale power systems are proposed. The control of power systems may require some centralization in the near future. The main purpose of the paper is the design of controller which is neither fully decentralized nor fully centralized, making it feasible, since only one remote signal is required for a controller. The sites where controllers should be applied and the most effective signals for each controller are determined by analyzing the input-output description of the system in the frequency of each mode of interest.

FM15-1 3420

An application of distributed air conditioning control network

Cheng, Hung-Ming — Industrial Tech. Research Inst.
Chen, Cheng-Yi — National Sun Yat-Sen Univ.
Cheng, Chi-Cheng — National Sun Yat-Sen Univ.
Chiu, George T.-C. — Purdue Univ.

In general, the air-conditioning system of a building accounts for almost 40% of the total energy consumption. Majority of the air-conditioning usage occurs during the day when the building is

occupied and the energy cost is higher. By shifting the portion of the peak hour usage to off-peak hours, one can potentially save up to 50% of the cost of energy for a typical office building. This paper presents a distributed building air conditioning control network that utilize the off-peak hours to make and store ice for peak hour cooling use. One advantage of the proposed approach is that current building temperature control units can be easily incorporated into the network, since the distributed control uses only the existing I/O information and open network communication protocol. The proposed network has the potential to include other environment control system into the existing temperature control system to form a complete building eco-control system to achieve more efficient use of available energy and to improve overall occupant comfort and efficiency. Experimental results demonstrated the effectiveness of the proposed distributed network control.

FM15-2 *
Withdrawn

FM15-3 3425
ER fluid dampers and their application in shock mitigation
Wu, Dong-Nan — Scientific Monitoring, Inc.
Jaw, Link C. — Scientific Monitoring, Inc.

The objective of this paper is to investigate the application of ER fluid dampers for shock protection of shipboard equipment. Several ER fluid dampers have been considered for this purpose. Dynamic models of these ER fluid dampers have been derived and important design parameters have been identified. A preliminary parametric study has been performed to compare the performance of these ER fluid dampers. A simple two degree of freedom system has been used to investigate the effect of ER fluid dampers on shock/vibration mitigation and their size and power requirement.

FM15-4 3430
A modified index for control performance assessment
Horch, Alexander — Royal Inst. of Tech.
Isaksson, Alf J. — Royal Inst. of Tech.

A control performance index which relates actual output variance to minimal achievable variance was first presented by Harris. In the present paper, a modification of that index is applied. Instead of comparing to minimum variance control - which corresponds to placing all closed-loop poles in the origin - one pole is placed using either control design guidelines or additionally available process knowledge. Some possible choices of the free closed-loop pole are discussed. Based on this modified closed-loop system, a performance index can be calculated which relates actual output variance to the minimum achievable variance using the modified closed-loop system. It is shown that for the calculation of this index no other information apart from the measured process output and the time-delay is necessary. The original Harris index and the proposed modified index are computed using data from industrial processes.

FM15-5 *
Withdrawn

FM15-6 3435
State-space local model networks based continuous-time GPC: application to induction motor
Hentabli, K. — Univ. de Picardie-Jules Verne

This paper presents a nonlinear control structure known as local controller network. The structure consists of a weighted combination of a number of individual continuous-time GPC controllers, each of which is valid locally in the state space of the plant. Local controller designs are based upon local models valid in operating regimes which correspond to N physical equilibrium points of the system. The design is carried out for the induction motor, and simulation results are included.

FM16-1 (I) 3440
Control of high-rise/high-speed elevators
Roberts, Randy — Otis Elevator Co.

An analytical framework for the development and evaluation of motion control system concepts for high-rise, high-speed elevators is presented in this paper. This problem definition, which includes a discussion of typical control system performance requirements, plant model dynamics and uncertainties, and control system robustness requirements, serves as a benchmark for the application and evaluation of advanced control approaches. Unique features of this problem include time varying dynamics, uncertain structural response, noncollocated control, sensor suite selection, and separable command and disturbance rejection control system requirements.

FM16-2 (I) 3445
Robust tracking for high-rise/high-speed elevators
Li, Jing — Duke Univ.
Niemann, David D. — Duke Univ.
Wang, Hua O. — Duke Univ.

This paper discusses the design of vertical motion control systems for high-rise/high-speed elevators. Two main performance requirements, tracking and releveling, are incorporated into the framework of an output regulation problem. By doing this, we design a single controller which satisfies both performance objectives. This design procedure is based on a local linear model of the elevator dynamics. Since the elevator dynamics change as a function of hoistway position, we utilize the concept of PDC (parallel distributed compensation) to generate a gain-scheduled controller which works for all floors. Simulation results have shown that the performance of this controller is also robust to the anticipated range of parameter uncertainty within the system.

FM16-3 (I) 3860
Identification and control of high-rise elevators
Venkatesh, S. R. — United Technologies Research Ctr.
Cho, Y. M. — United Technologies Research Ctr.

Building elevators for high-rise buildings pose significant engineering challenges for modeling, identification, validation and control of elevator systems. This paper focuses on integration of identification, validation and control for high-rise elevator systems. Unlike low rise towers, rope dynamics play a significant role in overall system dynamics. In the context of identification, long rope lengths manifest themselves in terms of low frequency lightly damped modes. In addition an elevator system has a large number of parameters to be identified. These factors make empirically based system identification difficult. We jointly solve the identification and model-validation problem by partly relying on intuition to reduce the complexity. We present a novel modal analysis approach to validation. We pose the following question: what are the optimal values of model parameters within predetermined ranges, required to validate the predominant mode and mode-shapes of the physics-based model with the experiment. Consequently, we have a system model for the high-rise elevator with parametric and non-parametric uncertainties in the context of control. High-rise elevator systems necessitate short shuttle times and good re-leveling capability. Therefore, position control for such high-rise elevator systems requires relatively high bandwidth despite parametric and non-parametric uncertainties in the system model. The problem can be naturally motivated as a robust performance m synthesis problem. It turns out that m synthesis approach effectively exploits the structure of the uncertainty to obtain robust performance. A typical classical design on the other hand is shown to lead to a closed-loop system that would compromise robust performance for stability.

FM16-4 (I) 3450
Multi-objective fuzzy control of high-rise/ high-speed elevators using LMIs
Tanaka, Kazuo — Kanazawa Univ.
Nishimura, Masataka — Kanazawa Univ.
Wang, Hua O. — Duke Univ.

This paper presents an LMI (linear matrix inequality) based fuzzy control approach to a high rise/high speed elevator. Motion control of the high rise/high speed elevators is a typical multi-objective control problem. To realize high performance, the multi-objective control problem should be effectively solved using a systematic way. This paper discusses a systematic design method for effectively realizing the multi-objective fuzzy control. First, the Takagi-Sugeno (T-S) fuzzy model is recalled. Secondly, the so-called parallel distributed compensation (PDC) is employed to design a fuzzy control system from the T-S fuzzy model. Next, to effectively solve the multi-objective control problem, LMIs that represent control performance such as decay rate, constraints on control input and output, robust stability, disturbance rejection, minimization of quadratic performance index and their mixed control problem are obtained. Convex optimization techniques based on LMIs are utilized to obtain feedback gains satisfying the above control performance. Finally, simulation results show the utility of the LMI based design procedure and realization of the multi-objective control.

FM16-5 (I) 3455

Trajectory generation of high-rise/high-speed elevators

Beldiman, Octavian — Duke Univ.
Wang, Hua O. — Duke Univ.
Bushnell, Linda G. — US ARO

The problem of generating the trajectory for high rise/ high speed elevators is investigated in this paper. Several approaches are used: open loop optimal control, closed loop optimal control and optimization algorithms. Each approach is accompanied by numerical simulations.

FM16-6 (I) 3870

Active control of a traveling medium with varying length

Ni, J. — Stevens Inst. of Tech.
Zhu, W. D. — Univ. of North Dakota
Huang, J. — Chinese Univ. of Hong Kong

Active control of a traveling medium with varying length is studied. The control device applies a pointwise force/moment fixed either in the space or to the medium. In the first case the control action is proportional to the local velocity/angular velocity of the point of the medium instantaneously located at the position of the control device. In the latter the control action is proportional to the total velocity/angular velocity of the point of attachment of the control device to the medium. The control laws are shown to stabilize the traveling medium during both retraction and extrusion, and can be easily implemented. Examples for a flexible arm through a prismatic joint and an elevator rope in a high rise building validate the analysis.

FP01-1 3460

Noncollocated adaptive-passive vibration control using self-tuning vibration absorbers

Buhr, Craig A. — Purdue Univ.
Franchek, Matthew A. — Purdue Univ.
Bernhard, Robert J. — Purdue Univ.

Presented in this paper is the development of a control law for tuning a variable stiffness vibration absorber to attenuate single frequency excitation in a noncollocated situation. The control law is comprised of two distinct parts. First, a +/- 90 degree phase condition between the motion of the vibration absorber and the location of interest is used to determine tuning direction. Next, a feedback based tuning strategy is used to precisely tune the vibration absorber for performance maximization. The feedback tuning strategy is based on the classical feedback structure of a regulating system. The absorber is tuned such that the accelerometer voltage resulting from the measurement of vibration of the point of interest is minimized. An experimental verification of this control law is shown.

FP01-2 3465

The design and implementation of robust strategies for active vibration control

Sadri, A. M. — Univ. of Manchester
Wynne, Richard J. — Sheffield Hallam Univ.
Wright, J. R. — Univ. of Manchester

Theoretical modelling of the vibration of a plate structure incorporating piezoelectric actuators is presented. The equations governing the dynamics of the plate, relating the strains in the piezoelectric elements to the strain induced in the system, are derived for isotropic plates using the Rayleigh-Ritz method. A technique for the optimal placement of piezoelectric actuators is developed using modal controllability and a Genetic Algorithm (GA) as the search engine. The model was used to design robust controllers (LQG and H-infinity) for a cantilever plate. The proposed controllers were then implemented with the measured results comparing favourably with those predicted from simulation.

FP01-3 3470

Boundary control of the axially moving Kirchhoff string

Shahruz, Shahram M. — Berkeley Eng. Research Inst.

In this note, the axially moving Kirchhoff string is considered. It is proved that this nonlinear string can be stabilized by the linear boundary control, which is the negative feedback of the transversal velocity of the string at one end.

FP01-4 3472

Boundary control for a general class of string models

Canbolat, H. — Clemson Univ.
Dawson, Darren M. — Clemson Univ.
Nagarkatti, S. — Clemson Univ.
Costic, B. — Clemson Univ.

In this paper, we study the control of an undamped, nonlinear string model with actuator dynamics at the boundary. Specifically, we develop a boundary controller which asymptotically stabilizes the out-of-plane displacement. The performance of the controller is illustrated via dynamic simulation.

FP01-5 3477

Experiments in two-axis vibration damping using inertial torques through momentum wheel control

Raab, Frank J. — Montana Tech.
Trudnowski, Daniel J. — Montana Tech.

In robotic systems where a micro-manipulator is mounted on the end of a long link, recent research has demonstrated the potential of vibration damping through inertial torques initiated by micro-manipulator modulation. In such systems, controllability concerns are raised when addressing multiple degrees of freedom, varying manipulator configurations, varying payload, and multiple long links. This paper presents experimental and theoretical results for active damping using inertial torques initiated by momentum (or torque) wheels mounted at the end of a flexible link. Such an approach provides controllability and control algorithm simplification advantages over micro-manipulator modulation methods with minimum added cost and weight. The paper presents a discussion on the advantages of torque wheel damping; conceptual, finite-element and system identification modeling results; and experimental bang-bang control results for two-degree of freedom damping under varying payloads.

FP01-6 3482

Vibrational control of underactuated mechanical systems: control design through the averaging analysis

Hong, Keum-Shik — Pusan National Univ.
Lee, Kang-Ryeol — Pusan National Univ.
Lee, Kyo-Il — Seoul National Univ.

An open loop vibrational control for underactuated mechanical systems with amplitude and frequency modulation is investigated. Since there is no direct external input to an unactuated joint, the dynamic coupling between the actuated and unactuated joint is utilized for controlling the unactuated joint. Feedback linearization has been performed to incorporate fully the known nonlinearities of the underactuated system considered. The actuated joints are firstly positioned to their desired locations, and then periodic oscillatory

inputs are applied to the actuated joints to move the remaining unactuated joints to their target positions. The amplitudes and frequencies of the vibrations introduced are determined through the averaging analysis. A systematic way of obtaining an averaged system for the underactuated system via a coordinate transformation is developed. A control design example of the 2R planar manipulator with a free joint with no brake is provided.

FP02-1 3487
Robust solutions to l1, l2 and l-infinity uncertain linear approximation problems using convex optimization
Hindi, Haitham — Stanford Univ.
Boyd, Stephen P. — Stanford Univ.

We present minimax and stochastic formulations of some linear approximation problems with uncertain data in R^n equipped with the Euclidean (l-2), Absolute-sum (l-1) or Chebyshev (l-infinity) norms. We then show that these problems can be solved using convex optimization. Our results parallel and extend the work of El-Ghaoui and Lebret on robust least squares, and the work of Ben-Tal and Nemirovski on robust conic convex optimization problems. The theory presented here is useful for desensitizing solutions to ill-conditioned problems, or for computing solutions that guarantee a certain performance in the presence of uncertainty in the data.

FP02-2 3492
Some conditions which make the constantly scaled H-infinity control synthesis problems convex
Asai, Toru — Univ. of California at Berkeley
Hara, Shinji — Tokyo Inst. of Tech.

In this paper, we present some conditions which make the LFT constantly scaled H-infinity control synthesis problems convex. Moreover, we show that a class of reduced order controller synthesis with scalings can be reduced to convex problems, as long as some of state variables are exactly available. If one of the conditions proposed in this paper holds, the constantly scaled H-infinity control synthesis problems can be solved efficiently as LMI problems. The results presented here include as special cases the existing results such as the state feedback and the full information problems.

FP02-3 3497
Guaranteed gain-phase margins for multi-model control
Luke, Robert A. — Univ. of New Mexico
Dorato, Peter — Univ. of New Mexico
Abdallah, Chaouki T. — Univ. of New Mexico

In the simultaneous performance design problem considered by the authors, linear-quadratic cost function state and control weightings are assumed. A single static state feedback gain is determined which minimizes the guaranteed-cost bound for each of the systems. It is now shown that subject to certain restrictions, the guaranteed-cost gain results in “non-fragile” system control: an infinite increasing gain margin, a decreasing gain margin of ½, and phase margins of sixty degrees for each system. The converse is also considered: given a guaranteed-cost gain, the set of all state and control weightings are found for which that gain remains optimal. This is possible through the use of a Kalman matrix identity.

FP02-4 3502
Issues on the discrete implementation of frequency domain controller design
Linde, E. K. — Purdue Univ.
Shin, Yung C. — Purdue Univ.

This paper discusses the issues pertaining to the discrete implementation of continuous frequency domain controller design. The effect of using an approximation of a delay term is discussed in conjunction with the phase error associated with the transformation of a continuous controller to its discrete counterpart. A direct discrete frequency domain design method based on loop shaping is presented as a technique to avoid the phase errors that occur with continuous-to-discrete transformations.

FP02-5 3504
The simplex architecture for safe on-line control system upgrades
Seto, Danbing — Carnegie Mellon Univ.
Krogh, Bruce H. — Carnegie Mellon Univ.
Sha, L. — Carnegie Mellon Univ.
Chutinan, A. — Carnegie Mellon Univ.

In this paper, we describe the Simplex architecture, a real-time software technology which supports the safe, reliable introduction of control system upgrades while the system is running. We introduce its basic structure in control systems, discuss its fault-tolerance feature, and investigate the control issues when the technology is employed. Application of the Simplex architecture is demonstrated for a plasma-enhanced chemical vapor deposition (PECVD) system, a standard process in semiconductor manufacturing. We conclude the paper with a discussion of the potential impact that the Simplex architecture can make on future control applications.

FP02-6 3509
Applying 03CACSD to control system design and rapid prototyping
Qiu, Xiaobing — ETH Swiss Fed. Inst. of Tech.
Schaufelberger, Walter — ETH Swiss Fed. Inst. of Tech.
Wang, Jiannong — ETH Swiss Fed. Inst. of Tech.
Sun, Youxian — Zhejiang Univ.

Modern control systems are of such complexity that control system design is achievable only with the aid of computer-based packages and tools. O3CACSD - an open, integrated environment for control system design, simulation, visualization, documentation, prototyping and testing is presented in this paper. Because it is developed with object-oriented method OMT (Object-Modeling Technique), O3CACSD is easy to extend and to maintain. An example of using O3CACSD in control education is given by a concrete example - rapid prototyping of control systems for a DC servo system.

FP03-1 3514
Multivariable controller tuning
Johansson, Karl Henrik — Lund Inst. of Tech.
James, Ben — Bank of America
Bryant, G. — Imperial College of Sci., Tech. & Med.
Astrom, Karl J. — Lund Inst. of Tech.

The problem of tuning individual loops in a multivariable controller is investigated. It is shown how the performance of a specific loop relates to a row in the controller matrix. Several interpretations of this relation are given. An algorithm is also presented that estimates the model required for the tuning via a relay feedback experiment. The algorithm does not need any prior information about the system or the controller. The results are illustrated by an example.

FP03-2 3519
Multiresolutional controller design
Clancy, Daniel J. — Ohio State Univ.
Ozguner, Umit — Ohio State Univ.

The framework necessary for achieving a multiresolutional control system is developed by this paper. This paper focuses on modeling each element of a control system using a best orthonormal wavelet packet basis and then determining the optimal controller using the same orthonormal wavelet packet basis or another related orthonormal wavelet packet basis. A theorem for designing a wavelet packet controller which minimizes the 2-norm sensitivity function for a single-input single-output (SISO) system is presented. A theorem for designing a wavelet packet controller which minimizes the 2-norm mixed sensitivity function for a SISO system is also presented. Multiresolutional controller design examples are presented and compared with discrete H-2 controllers.

FP03-3 3524
Multivariable PID controller design based on the direct Nyquist array method
Ho, W. K. — National Univ. of Singapore
Xu, Wen — National Univ. of Singapore

The gain and phase margins design for SISO PID controllers is extended to the multivariable system Nyquist array. The design method allows the user to specify the robustness and performance of the system through gain and phase margin specifications. The automated design procedure given in this paper is well suited for implementing self-tuning PID control for multivariable processes. A laboratory implementation is given in the paper to demonstrate the design method.

FP03-4 3529
On logarithmic complementary sensitivity integrals for MIMO systems
Chen, Jie Univ. of California at Riverside

Bode and Poisson type integral inequalities for the complementary sensitivity function are derived in this paper for multi-input multi-output systems, which generalize earlier work of a similar nature but only applicable to single-input single-output systems. The results characterize how open loop nonminimum phase zeros may adversely affect a system's performance, and how each of the zeros may couple with other nonminimum phase zeros and unstable poles to impose a severe limitation on the achievable performance quantified by the complementary sensitivity function, to which the zero directions are seen to play a central role.

FP03-5 3531
Simultaneously stabilizing controller design for a class of linear plants
Gundes, A. Nazli Univ. of California at Davis
Kabuli, M. G. Univ. of California at Davis

All simultaneously stabilizing controllers are characterized for a class of linear, time-invariant, multi-input multi-output plants. These plants all have poles at zero but they have no other unstable poles.

FP03-6 3533
A simultaneous observer-based controller
Fonte, Christophe CRAN-CNRS
Zasadzinski, Michel LARAL
Darouach, Mohamed CRAN-CNRS

In this note, a parametrization of all functional observer-based controllers that stabilize a given plant is proposed. This parametrization is used to design simultaneous functional observer-based controllers for two plants and to derive some sufficient conditions and some necessary conditions for the existence of simultaneous functional observer-based controllers. These sufficient conditions express the existence of simultaneous functional observer-based controllers in function of the unstable zero structure of the difference of the two plants. The necessary conditions set that the existence of simultaneous functional observer-based controllers depends on two Q-parameters. Then, it is shown that the existence conditions of a simultaneous functional observer-based controller are not exactly a simple concatenation of the existence conditions of a simultaneous controller and the existence conditions of a simultaneous functional observer. Finally, a design procedure to compute simultaneous functional observer-based controllers is presented.

FP04-1 *
Reliable and robust H-infinity control for state delayed systems
Yan, Yonghong Northeastern Univ.
Zhang, Si-Ying Northeastern Univ.

FP04-2 3538
An explicit formula for a robust controller for SISO systems with unknown delays
Olbrot, Andrzej W. Wayne State Univ.

An explicit formula is presented for a robust controller for a SISO plant with unknown time delay and a nonminimum-phase transmission zero. For a known transmission zero, the controller has a remarkable property of robust stability and zero steady-state error for any perturbation of the time delay in the plant transfer function. Such property never occurs for PID and other traditional controllers due to infinite or large zero frequency gain. In case of unknown zero, the robust stability is maintained for arbitrary delay perturbations and the steady-state error can be estimated from bounds on the location of that zero.

FP04-3 3540
Shaping structure dynamics with truncation error-bounded reduced-order models for integrated mechanism/control design
Savant, Shrikant Massachusetts Inst. of Tech.
Asada, Haruhiko Massachusetts Inst. of Tech.

A method for shaping the structure dynamics of mechatronic systems using truncation-error bounded reduced-order models is developed and applied to the design of a heavy-duty robot with non-collocated sensors and actuators. Modeling is a critical issue in the integrated approach to design and control of mechanisms. The model required for mechanical design is different from the one for control design. The former is geometric and parametric with respect to the dimensions of individual parts. Dynamic models derived from such geometric models are in general of high order. The model for control design must be an explicit input-output causal form with an appropriate system order. As the mechanical structure is altered during this integrated design process, the validity of the dynamic model is difficult to preserve due to the strong influence of design parameter changes on the model truncation error. Even the order of the model may change as design parameters change. In this paper a method has been developed for improving structural performance while maintaining validity of the reduced-order models by upper-bounding the truncation error. This method makes use of the Hankel singular values and sensitivity Jacobians. Desired changes to dynamics are obtained by altering design parameters within the subspace where the Hankel singular values corresponding to unmodeled dynamics may be kept lower than a certain limit, hence upper-bounding the truncation-error and preserving the validity of the reduced-order model. The method is then applied to the design of a heavy-duty robot with non-collocated sensors and actuators. With this method, since the truncation-error of the structural model is upper-bounded, a controller can be designed so as to guarantee robustness.

FP04-4 3545
Piecewise-linear robust control of systems with input constraints
Henrion, Didier LAAS-CNRS
Garcia, Germain LAAS-CNRS
Tarbouriech, Sophie LAAS-CNRS

Robust stabilization of an uncertain system subject to input constraints is addressed without making open-loop stability assumptions. A local approach is taken to find a robust control law and a set of initial conditions that can be stabilized. A piecewise-linear control law generated by a parametrized algebraic Riccati equation of the H-infinity control theory is described. Once system trajectories are sufficiently close to the origin, a certain performance level is ensured through a guaranteed cost control. A simple and tractable design algorithm is proposed and illustrated by a numerical example.

FP04-5 3550
Robust control of a class of sampled-data systems against LTI uncertainties
Toivonen, Hannu T. Abo Akademi Univ.
Sagfors, Mats F. Abo Akademi Univ.

The robust stability in sampled-data control is studied for LTI uncertainties. A class of problems, which allows an exact characterization of the robust sampled-data problem in terms of a discrete H-infinity problem is considered. In the problems studied certain restrictions on the product of the uncertainty weight and the antialiasing prefilter are imposed. In return, a significant simplification of the solution is achieved, in which robust stability to LTI perturbations can be formulated as a discrete H-infinity problem.

FP04-6 3555

Robust stability of a diamond of multivariate polynomials

Ramirez-Sosa Moran, Marco Ivan — CINVESTAV-IPN
Kharitonov, V. L. — CINVESTAV-IPN

In this paper we present an extension of the extreme point result for robust stability of a diamond of polynomials, Barmish et al., for the multivariate case, with the main result that a diamond of m-variate polynomials with real coefficients is stable if and only if a set of distinguished extreme polynomials are stable.

FP05-1 3559

Rational basis functions for robust identification from frequency and time domain measurements

Akcay, Huseyin — Tubitak Marmara Research Centre
Ninness, Brett M. — Univ. of Newcastle

This paper investigates the use of general bases with fixed poles for the purposes of robust estimation. These bases, which generalize the common FIR, Laguerre and two-parameter Kautz ones, are shown to be fundamental in the disc algebra provided a very mild condition on the choice of poles is satisfied. It is also shown, that by using a min-max criterion, these bases lead to robust estimators for which error bounds in different norms can be explicitly quantified. The key idea facilitating this analysis is to re-parameterize the chosen model structures into a new one with equivalent fixed poles, but for which the basis functions are orthonormal in H2.

FP05-2 3564

Computing output prediction bounds using ellipsoidal parameter bounding

Maksarov, D. — Silsoe Research Institute
Chalabi, Z. S. — Silsoe Research Institute

The paper presents an algorithm for output prediction in linear ARX models by computing bounds on future output values. Ellipsoidal bounding is used to compute a set of future outputs consistent with the model structure, noise bounds and observed data. Simulation results are presented.

FP05-3 3566

On the worst-case divergence of the least-squares algorithm

Akcay, Huseyin — Tubitak Marmara Research Centre
Ninness, Brett M. — Univ. of Newcastle

In this paper, we provide a H-infinity-norm lower bound on the worst--case identification error of least-squares estimation when using FIR model structures. This bound increases as a logarithmic function of model complexity and is valid for a wide class of inputs characterized as being quasi-stationary with covariance function falling off sufficiently quickly.

FP05-4 3570

The least squares: output error sensitivity and the constrained logarithmic algorithm

Bai, Er-Wei — Univ. of Iowa
Ye, Yinyu — Univ. of Iowa

It is shown in the paper that while robust in terms of the average output error, the least squares estimate is sensitive to outliers with respect to the maximum output error. In fact the worst-case output error of the least squares can go unbounded. Then, a constrained logarithmic least squares for system identification is applied to solve problem.

FP05-5 3575

Optimal sensor configuration for complex systems

Sadegh, Payman — Tech. Univ. of Denmark
Spall, James C. — Johns Hopkins Univ.

The paper considers the problem of sensor configuration for complex systems with the aim of maximizing the useful information about certain quantities of interest. Our approach involves two fundamental contributions: (1) definition of an appropriate optimality criterion or performance measure, and (2) description of an efficient and practical algorithm for achieving the optimality objective. The criterion for optimal sensor configuration is based on maximizing the overall sensor response while minimizing the correlation among the sensor outputs, so as to minimize the redundant information being provided by the multiple sensors. The procedure for sensor configuration is based on the powerful simultaneous perturbation stochastic approximation (SPSA) algorithm. SPSA avoids the need for detailed modeling of the sensor response by simply relying on observed responses as obtained by limited experimentation with test sensor configurations. We will illustrate the approach with the optimal placement of acoustic sensors for signal detection in structures. This includes both a computer simulation study for an aluminum plate, and real experimentations on a steel I-beam.

FP05-6 3580

Set-valued nonlinear estimation using the Galerkin approximation

Kenney, John D. — Brigham Young Univ.
Beard, Randal W. — Brigham Young Univ.
Stirling, Wynn C. — Brigham Young Univ.

A set-valued state estimator for nonlinear dynamic systems is presented. The estimator uses the Galerkin approximation to solve Kolmogorov's equation for the diffusion of a continuous-time, continuous-state nonlinear system, as well as for implementing discrete time updates of noisy measurements. This filtering of the state is accomplished for a convex set of distributions simultaneously and a functional representation of the set of resulting means is provided at any desired time instance.

FP06-1 3585

Parameter identification for an autonomous 11th order nonlinear model of a physiological process

Rundell, Ann E. — Purdue Univ.
DeCarlo, Raymond A. — Purdue Univ.
Doerschuk, P. — Purdue Univ.
HogenEsch, H. — Purdue Univ.

This paper sets forth and illustrates some techniques for parameter identification (PId) of a nonlinear state model that approximates the dynamical behavior of the humoral immune response of a human to Haemophilus influenzae Type-b. The natural physiological time-separation of the primary, late follicular, and secondary immune responses of this biological process allows us to divide the PId problem into a sequence of smaller PId sub-problems. To reduce the dimension of the PId even further, coupling effects are minimized or eliminated by temporarily replacing variables and/or certain other functions of variables by approximate a priori known time functions called exogenous inputs. This sequence of low dimensional PId problems entails matching a set of one or two parameters at each step to a time-attribute pair defined as a maximum or minimum measured concentration level in a given time window. The identification sub-problem solution reduces to the inverse of an approximate local parameter-to-measurement map. The techniques presented herein are applicable to other nonlinear systems which exhibit similar time-sequenced properties.

FP06-2 3590

Parameter subset identification by recursive least squares

Pizarro, O. — Univ. de Concepcion
Sbarbaro, Daniel G. H. — Univ. de Concepcion

A technique for recursive least squares (RLS) identification of only a subset of parameters of a linear model is presented. Based on the decomposition of the least squares (LS) problem, an exact solution and a recursive approximation are developed. Identification of a subset of parameters is useful in adaptive control techniques based on cost function identification.

FP06-3 3592

Modeling and parameter identification of ice-affected streamflow

Holtschlag, David J. — U.S. Geological Survey
Grewal, M. S. — California State Univ. at Fullerton

An extended Kalman filter was developed to automate the real-time estimation of ice-affected streamflow. The filter uses routine measurements of stream stage, air temperature, and the open-water relation between stage and streamflow to compute ice-affected streamflow. The filter accommodates three dynamic modes of ice effects: sudden formation/ablation, stable-ice conditions, and eventual elimination. The utility of the filter was evaluated by applications to historical data from two long-term streamflow-gaging stations, St. John River at Dickey, Maine and Platte River at North Bend, Nebr. Results indicate that the filter is stable and that site-specific parameters converged for both stations, producing streamflow estimates that closely match published values. Implementation of the filtering technique would provide a basis for quality-assuring real-time data on ice-affected streamflow.

FP06-4 3597

Parametric identification of closed-loop linear systems using cyclic-spectral analysis

Tontiruttananon, Channarong Auburn Univ.
Tugnait, Jitendra K. Auburn Univ.

The problem of closed-loop system identification given noisy time-domain input-output measurements is considered. It is assumed that the various disturbances affecting the system are zero-mean stationary whereas the closed-loop system operates under an external cyclostationary input which is not measured. Noisy measurements of the (direct) input and output of the plant are assumed to be available. The closed-loop system must be stable but it is allowed to be unstable in open-loop. Two new identification algorithms are proposed using cyclic-spectral analysis of noisy input-output data. For both approaches, the open-loop transfer function is first estimated using the cyclic-spectrum and cyclic cross-spectrum of the input-output data. These transfer function estimates are then used as “data” for the proposed algorithms. Both classes of parameter estimators are shown to be weakly consistent in any stationary and a class of cyclostationary noise (both at input as well as output). Computer simulation examples are presented in support of the proposed approaches.

FP06-5 3602

Optimal state estimation and parameter identification of MIMO uncertain discrete stochastic linear systems

Rusnak, Ilan Rafael

The problem of optimal simultaneous state estimation and parameters identification of MIMO stochastic discrete linear time-invariant systems is formulated. The state and parameters observability form is introduced. This new representation of MIMO linear time-invariant systems enables application of the existing optimal estimation theory for linear stochastic time-varying systems to the solution of the problem.

FP06-6 3607

Parameter decoupling for transfer function identification during quasi-harmonic operation

Pearson, Allan E. Brown Univ.

Using a frequency domain model arising from Fourier moment functionals of the Shinbrot type, it is shown how a particular decoupling can be exploited in estimating parameters that characterize the numerator and denominator transfer function polynomials when sinusoidal probing signals are used during an otherwise transient or nonstationary state of operation. Potential applications include frequency analyses of lightly damped systems for which establishing steady state or stationary operation may require unreasonably long settling times.

FP07-1 3612

The Zames-Falb IQC for critically stable systems

Jonsson, Ulf T. Massachusetts Inst. of Tech.
Megretski, Alexandre Massachusetts Inst. of Tech.

A feedback interconnection of a neutrally stable linear time-invariant system and a nonlinearity with $0<xf(x)<kx^2$ is called critical since the worst case linearization is at best neutrally stable. This makes the stability analysis of such systems particularly hard. It will be shown that an integrator and a sector bounded nonlinearity can be encapsulated in a bounded operator that satisfies several useful integral quadratic constraints. This gives powerful tools for stability analysis of critically stable systems.

FP07-2 3617

Bifurcation analysis and control for surge model via the projection method

Gu, Guoxiang Louisiana State Univ.
Sparks, Andrew G. Wright Lab.
Kang, Wei Naval Postgraduate School

A bifurcation approach is adopted to analyze and control the surge model for axial flow compressors. An explicit expression is obtained for the first nonzero coefficient of the characteristic exponents of the periodic solutions born from the Hopf bifurcation associated with surge. The sign of this coefficient determines stability of the surge model at the criticality. Local nonlinear feedback control laws are then developed to stabilize the Hopf bifurcation associated with surge. Both quadratic and cubic state feedback control laws are investigated. Feedback stabilization using output measurement such as pressure rise is also studied where stabilizing gains are characterized that can be used for synthesis of surge control laws.

FP07-3 3622

On the nonlinearly structured stability radius problem

Yan, Wei-Yong Nanyang Tech. Univ.
Lam, James Univ. of Hong Kong

This paper considers the problem of finding a perturbation matrix with the least spectral norm such that a matrix-valued function becomes singular, where the dependence of the function on the perturbation is allowed to be nonlinear. It is proved that such a problem can be approximated by a smooth unconstrained minimization problem with compact sublevel sets. A computational procedure proposed based on this result is demonstrated to be effective in both linear and nonlinear cases.

FP07-4 3627

Practical stability of discrete event systems using Lyapunov methods

Retchkiman, Zvi Instituto Politecnico Nacional

This paper deals with the practical stability problem of discrete event systems using Lyapunov methods. A new analysis methodology based on Lyapunov functions and comparison principles is presented. This approach allows to get immediate information about the system's stability in a very easy and convenient way. By proving practical stability one is allowed to preassigned the bound on the system's dynamics performance. Two examples where the methodology presented is applied are given.

FP07-5 3629

The development of anti-windup scheme and stick-slip compensator for time delay control

Chang, Pyung H. Korea Adv. Inst. of Sci. & Tech.
Park, Suk H. Korea Adv. Inst. of Sci. & Tech.

Time Delay Control (TDC), owing to its simplicity and unusual performance against parameter variations and disturbances, has been noted and recognized as a promising technique. We have observed, however, that in the presence of the so-called hard nonlinearity such as saturation or static friction, TDC reveals some problems commonly found in other methods like PID control or disturbance observer. Specifically, when the system has a saturation limit, TDC shows the windup phenomenon; when static friction and stribeck effect are dominant, TDC reveals the stick-slip phenomenon. In this paper, we have reported these phenomena associated with TDC, presented their causes, and proposed their remedies. Specifically, through analysis, simulation, and experiment, we have shown that both the phenomena cause serious degradations in control performance; that they result from a common cause, the inherent integral effect in TDC; and that the proposed compensators

are effective enough to handle the phenomena. In addition to their effectiveness, the proposed compensators have remarkable simplicity and efficiency that matches the positive attributes of the original TDC.

FP07-6 3634
An extended stability theorem for nonlinear systems subject to slowly varying exogenous signals
Wang, Yibing Tsinghua Univ.
Han, Zeng-Jin Tsinghua Univ.

This paper deals with the stability properties of nonlinear systems subject to slowly varying exogenous signals. First, a well-known stability result of linear time-varying systems is improved. Second, an extended stability Theorem is established for nonlinear systems where exogenous signals are slowly-varying in the sense of moving-average. Finally, the application of this extended theorem to automated vehicle platoons is outlined.

FP08-1 3639
On the use of switched linear controllers for stabilizability of implicit recursive equations
Nesic, Dragan Univ. of California at Santa Barbara
Skafidas, E. Univ. of Melbourne
Mareels, Iven Univ. of Melbourne
Evans, Robin J. Univ. of Melbourne

Stabilizability of implicit recursive equations is investigated. These equations arise naturally in the context of output dead-beat control for systems described by NARMAX models. Due to non-uniqueness of the solutions of these equations a special kind of a constrained stabilizability problem is considered. We take a hybrid switching control approach in testing the existence of a locally stabilizing controller. A method to design the stabilizing controller is also presented.

FP08-2 3644
Robust adaptive stabilization with multiple H-infinity uncertainty models and switching
Rangan, Sundeep Univ. of Michigan
Poolla, Kameshwar Univ. of California at Berkeley

In this paper, we consider a simple robust adaptive stabilization problem based on an H-infinity uncertainty model with a discrete unknown parameter. In the proposed problem formulation, the unknown plant is assumed to belong to one of N possible uncertainty models, where each model is described by a known, linear nominal plant with H-infinity bounds on the unmodeled dynamics. We show that if each of the models can be robustly stabilized with a linear time-invariant (LTI) controller, then there exists a single adaptive (possibly nonlinear and time-varying) controller that simultaneously robustly stabilizes all the N possible uncertainty models. The adaptive controller can provide the same level of stability robustness as the LTI controllers, and introduces, at most, a bounded transient in the output. Our approach is based on a simple switching algorithm and a novel application of H-infinity filtering methods.

FP08-3 3649
Reconfiguration and scheduling in flight using quasi-LPV high-fidelity models and MBPC control
Huzmezan, Mihai Cambridge Univ.
Maciejowski, Jan M. Cambridge Univ.

This paper describes advances towards reconfiguration and scheduling in flight control systems using high fidelity models expressed in a quasi-LPV form, Fault Detection and Isolation (FDI), model approximation/simplification and constrained Model Based Predictive Control (MBPC). The strategy is applied to a well known missile example.

FP08-4 3654
Harmonic analysis of nonlinear and uncertain systems
Rantzer, Anders Lund Inst. of Tech.
Megretski, Alexandre Massachusetts Inst. of Tech.

This paper is devoted to performance analysis of nonlinear and uncertain systems using integral quadratic constraints. In particular, we consider sinusoidal excitation of a system involving a nonlinearity satisfying a conic bound. The analysis is performed in three steps. Firstly, it is proved for a range of frequencies of excitation, that the output of the system converges to a periodic signal, with a period length related to the period of excitation. Secondly, uniqueness of the limiting orbit is proved. Finally, the magnitudes of the output harmonics are estimated. In all three steps, different sets of integral quadratic constraints are available.

FP08-5 3659
Quadratic stabilization and control of piecewise-linear systems
Hassibi, Arash Stanford Univ.
Boyd, Stephen P. Stanford Univ.

We consider analysis and controller synthesis of piecewise-linear systems. The method is based on constructing quadratic and piecewise-quadratic Lyapunov functions that prove stability and performance for the system. It is shown that proving stability and performance, or designing (state-feedback) controllers, can be cast as convex optimization problems involving linear matrix inequalities that can be solved very efficiently. A couple of simple examples are included to demonstrate applications of the methods described.

FP08-6 3665
Robust switching missile autopilot
Brugarolas, Paul B. Univ. of Southern California
Fromion, Vincent Univ. di Roma
Safonov, Michael G. Univ. of Southern California

A robust switching controller is developed by application of the unfalsified control concept. Key ideas and implementation issues are discussed. In particular, a new performance specification and a falsification algorithm are developed. Simulation results are provided using a nonlinear model for the missile.

FP09-1 3670
A modified internal model control scheme with simplified design and implementation
Wang, Qing-Guo National Univ. of Singapore
Zhang, Yu National Univ. of Singapore
Zhang, Yong National Univ. of Singapore

This paper proposes a modified internal model control scheme. The proposed scheme does not require explicit transfer function model of the plant. The design procedure is simple and the parameters of the controller are given in analytic formula. The resulting controller is of fixed-order form, which makes implementation easy. Simulation shows that the proposed scheme gives consistent and satisfactory performance for a large class of plants.

FP09-2 3672
Decoupling internal model control for multivariable systems with multiple time delays
Wang, Qing-Guo National Univ. of Singapore
Zhang, Yu National Univ. of Singapore
Chiu, Min-Sen National Univ. of Singapore

In this paper, the decoupling problem with stability for linear multivariable processes with multiple time delays is considered and the internal model control scheme is adopted. All the controllers which solve the problem and the resultant closed-loop systems are characterized in terms of their unavoidable time delays and non-minimum phase zeros. According to such characteristics, a control design for best achievable performance is presented and further simplified with the help of model reduction to obtain an easy-to-implement yet good approximation to the theoretical solution of generally high complexity. Numerical and practical examples are given to illustrate our analysis and design.

FP09-3 3677
The theory and design of adaptive internal model control schemes
Datta, Aniruddha Texas A&M Univ.

Xing, Lei Texas A&M Univ.

This paper develops a systematic theory for the design and analysis of adaptive internal model control schemes. The ubiquitous Certainty Equivalence principle of adaptive control is used to combine a robust adaptive law with robust internal model controllers to obtain adaptive internal model control schemes with provable guarantees of stability and robustness. Specific controller structures considered include those of the model reference, “partial” pole placement, and H2 and H-infinity optimal control types. The results here not only provide a theoretical basis for analytically justifying some of the reported industrial successes of existing adaptive internal model control schemes but also open up the possibility of synthesizing new ones by simply combining a robust adaptive law with a robust internal model controller structure.

FP09-4 3685

Robust internal model servo control with control input saturation

Yamada, Kou Yamagata Univ.

In this paper, we propose a design method of antiwindup servo control based on Internal Model Control structure by using the idea of named Internal Perturbed Model Control.

FP09-5 3687

Robust run-to-run control for semiconductor manufacturing: an internal model control approach

Adivikolanu, Sudhakar Univ. of Maryland
Zafiriou, Evanghelos Univ. of Maryland

This paper presents the design of Run to Run (RtR) controllers using the Internal Model Control (IMC) structure. In RtR control the input recipe for a run is determined using the in-situ and ex-situ measurements of past runs. RtR controllers utilizing linear Response Surface Models (RSM) are considered. The RtR controllers are designed to be robust with respect to modeling error and incorporate measurement delays. The RtR IMC filter design is modified to compensate for process drifts, and to account for the inherent unit measurement delay that exists for RtR control. A detailed robustness analysis is presented to obtain good stability and performance. These conditions are used to a priori predict achievable process performance. Simulations show that the developed RtR controllers are able to control the process even in the presence of sudden disturbances, measurement delays and reactor aging. Simulations also show that they perform better than exponentially weighted moving average controllers. Since for many processes in semiconductor manufacturing the RtR controllers used are often based on linear RSM models, the current approach has wide applicability.

FP09-6 3692

Reference governors and predictive control

Rossiter, J. Anthony Loughborough Univ.
Kouvaritakis, Basil Oxford Univ.

The reference governor (RG) approach to constraint handling has been proposed as an efficient but perhaps suboptimal alternative to predictive control (MBPC). Here we illustrate that the basic construction of RG and MBPC schemes is the same and the only difference is the choice of performance index.

FP10-1 3694

A new proof of the Jury test

Keel, Lee H. Tennessee State Univ.
Bhattacharyya, Shankar P. Texas A&M Univ.

The problem of determining the root distribution of a real polynomial with respect to the unit circle, in terms of the coefficients of the polynomial, was solved by Jury in 1964. The calculations were presented in tabular form (Jury's table) and were later simplified by Raible in 1974. This result is now classical and is as important in the stability analysis of digital control systems as its continuous time counterpart, the Routh Hurwitz criterion is for the stability analysis of continuous time control systems. Most texts on digital control state the Jury test but avoid giving the proof. In this paper we give a simple, insightful and new proof of the Jury test. The proof is based on the behaviour of the root-loci of an associated family of polynomials. The proof reveals clearly the mechanism underlying the counting of the roots within and without the unit circle and this is illustrated with an example.

FP10-2 3699

Nonlinear discrete-time systems: constrained optimization and application of nonquadratic costs

Lyshevski, Sergey Purdue Univ. at Indianapolis

In this paper, the constrained optimization problem is researched and solved for nonlinear discrete-time systems. The Hamilton-Jacobi theory is applied to design a new class of bounded controllers, and an innovative nonquadratic performance index is minimized. These innovations extend the optimization theory. In particular, the reported framework ensures straightforward analytical and numerical results, and the presented concept significantly reduces the computational conservatism of conventional methods. It is shown that for open-loop unstable systems, the constrained optimization problem is solvable if the sufficient conditions are satisfied. This leads to the application of the admissibility framework, and the maximal positively invariant admissible set of stability S is found applying the Lyapunov stability criteria. The resulting closed-loop nonlinear system with bounded controller evolves in X. The constrained optimization problem is solvable via bounded control, and stability is guaranteed if XcS . The results are verified and illustrated solving the motion control problem for a high-performance aircraft.

FP10-3 3704

Optimal hold functions for MDCS sampled-data problems

Mirkin, Leonid Technion-Israel Inst. of Tech.
Palmor, Zalman J. Technion-Israel Inst. of Tech.

The issue of whether there is any benefit in using a generalized sampled-data hold (GSDH) over the conventional zero-order hold is one of the central issues in sampled-data control. Usually, the design of GSDH is based on pure discrete specifications. Loosely speaking, such an approach offers an opportunity to improve discrete-time system performance considerably, yet at the expense of a deterioration in the continuous-time one. Although in many applications discrete-time requirements may be to some extent more important, the degradation of the continuous-time performance under the "discrete" design of GSDH is usually not acceptable. In this paper we propose a new approach to the design of GSDH, which is based on the search of a reasonable tradeoff between the deterioration of continuous-time performance and the improvement of the discrete-time one. To this end, the design problem is formulated as the one with mixed discrete/continuous specifications (MDCS), allowing discrete and analog requirements to be accounted for in a natural manner. In the paper both H2 and H-infinity MDCS designs of GSDH are addressed.

FP10-4 3709

Stability analysis of a class of nonlinear multirate digital control systems

Hu, Bo Univ. of Notre Dame
Michel, Anthony N. Univ. of Notre Dame

We consider multirate digital control systems which consist of an interconnection of a continuous-time nonlinear plant (described by ordinary differential equations) and a digital lifted controller (described by ordinary difference equations). The input to the digital controller consists of the multirate sampled output of the plant and the input to the continuous-time plant consists of the multirate hold output of the digital controller. In the present paper we show that when quantizer nonlinearities are neglected, then under reasonable conditions (which exclude the critical cases), the stability properties (in the Lyapunov sense) of the trivial solution of the nonlinear multirate digital control system can be deduced from the stability properties of the trivial solution of its linearization. When quantizer nonlinearities are not neglected, corresponding results can be

established for Lagrange stability (resp., boundedness of solutions) rather than Lyapunov stability of an equilibrium.

FP10-5 3714
Lp analysis of nonsynchronous multirate sampled-data systems: continuity property and robustness
Ito, Hiroshi — Kyushu Inst. of Tech.

This paper focuses on multi-rate sample-data control systems with nonsynchronous decentralized controllers whose sampler-and-hold elements in different stations update their state independently of each other. The effect of nonsynchronous phase distribution on L-p worst-case performance is analyzed. It is shown that the performance measure is a continuous function of the phase shift provided that anti-aliasing filters are located appropriately. Slight perturbation of the phase only results in a slight degradation or improvement of the closed-loop performance. Furthermore, the analysis of the continuity property enables us to estimate how robust the performance is against the phase perturbation.

FP10-6 3719
Multimodel robust control by fast output sampling - an LMI approach
Werner, Herbert — Ruhr-Univ. of Bochum

An LMI approach to robust multimodel controller design is proposed. The fast output sampling control law considered here allows in theory to realize the effect of a robust state feedback gain simultaneously for a family of linear models. In practice, there are two reasons why exact realization of state feedback may not be desirable or even impossible: noise sensitivity due to large output feedback gains, and poor error dynamics. An LMI formulation of the design problem allows to approximate a robust state feedback design by fast output sampling, in a way that closeness to the original design can be traded against reducing these deteriorating effects. The proposed method is illustrated by a multivariable design example and experimental results.

FP11-1 3724
Robust adaptive control for discrete time-varying systems
Yin, Bin — Southeast Univ.
Feng, Chun-Bo — Southeast Univ.

A method for designing adaptive control linear discrete TV systems is proposed in this paper. The control scheme is formed on the basis of the concept of sliding mode control. To avoid the chattering phenomenon, we use two compensation terms to replace the switching signal. Simulation results show the effectiveness of the proposed method.

FP11-2 3726
Controller design for linear time varying systems by backstepping
Yu, Xinghuo — Central Queensland Univ.
Wu, Yu-Qiang — Qufu Normal Univ.
Chu, Xuedao — Qufu Normal Univ.

A new model reference adaptive control scheme based on nonlinear backstepping approach is proposed for linear time varying systems. The main idea of this design scheme is to construct a new tracking error dynamics to perform the nonlinear backstepping design. By the proper choices of the controller parameters and the intermediate control functions, the output tracking error can be made sufficiently small.

FP11-3 3728
Positively invariant set of RFDE with applications to linear systems with time-varying input delays
Hou, Chunhai — Zhejiang Univ.
Qian, Jixin — Zhejiang Univ.

Positively invariant set of retarded functional differential equation (RFDE) with perturbations is investigated. As the application of results obtained for RFDE, the state positively nonsymmetrical invariant set for linear systems with nonlinear time-varying input delay is first introduced, and sufficient conditions of the state positively nonsymmetrical invariant set for such systems are presented.

FP11-4 3730
Robust memoryless H-infinity control for uncertain linear time-delay systems
Su, Hongye — Zhejiang Univ.
Wang, Jingcheng — Zhejiang Univ.
Chu, Jian — Zhejiang Univ.

The problem of quadratic stabilization and robust H-infinity controller design for a class of linear time-varying uncertain dynamic systems with delayed state and control are studied via Riccati equation approach in this paper. A static state feedback controller which stabilizes the plant and reduces the effect of the disturbance input on the controlled output to a prescribed levels for all admissible time-varying uncertainties is presented and a sufficient condition for the existence of robust H-infinity controller is derived. Then the sufficient condition is transformed into a Linear Matrix Inequality (LMI) problem and the control law can be obtained by solving LMI.

FP11-5 3732
Generalized hold function design for periodically time-varying systems
Chen, Min-Shin — National Taiwan Univ.

Most control designs for periodically time-varying systems use either full state feedback or observer-based state feedback. In this paper, it is shown that static output feedback control is sufficient for the exponential stabilization of a periodical system under both the controllability and observability assumptions. In fact, by incorporating a new generalized hold function in the control design, one is able to arbitrarily shift all the Poincare exponents of the periodical system. Most importantly, the control signal is guaranteed to be continuous in time while the control signal from previous designs may be discontinuous.

FP11-6 3737
Input-output block decoupling of linear time-varying singular systems
Wang, Xiaohua — Northeastern Univ.
Liu, Xiaoping — Northeastern Univ.
Jing, Yuanwei — Northeastern Univ.

In this paper, we discuss the input-output block decoupling problem by state feedback for linear time-varying singular systems. An algorithm is developed such that the system can be expressed in a simple form. A time-varying feedback law is then constructed, which ensures, under appropriate conditions, that the closed-loop system is regular, impulse free, and noninteractive. Sufficient and necessary condition for the solvability of the input-output block decoupling problem is derived.

FP12-1 3742
A practical algorithm for designing nonlinear H-infinity control laws
Beard, Randal W. — Brigham Young Univ.
McLain, Timothy W. — Brigham Young Univ.

In this paper we describe a novel approximation method for the Hamilton-Jacobi-Isaacs (HJI) equation that results in feedback control. The approximation is accomplished via a two-step successive Galerkin approximation scheme. An application of the technique to the control of the forward motion of an underwater vehicle is described.

FP12-2 3744
A computational issue in nonlinear H-infinity control
Hu, S. S. — Drexel Univ.
Yang, Pao-Hwa — Combined Service Forces
Chang, Bor-Chin — Drexel Univ.

Ball, Helton, and Walker (BHW) derived nonlinear H-infinity controller formulas with the assumption implying that no stable mode uncontrollable from the exogenous input. In this paper, we address the numerical difficulty encountered by BHW's controller formulas

when the assumption is not satisfied. Next, we propose a modified nonlinear H-infinity controller and successfully remove the numerical difficulty.

FP12-3 3746
Design and performance analysis of a direct adaptive controller for feedback linearizable systems

Zhang, T. National Univ. of Singapore
Ge, S. S. National Univ. of Singapore
Hang, Chang Chieh National Univ. of Singapore

This paper presents a new direct adaptive controller based on multilayer neural networks (MNNs) for a class of feedback linearizable systems. The designed controller ensures that the system output tracking error converges to a small neighborhood of zero, while the stability of the closed-loop systems is guaranteed. In addition, the transient performance is analytically quantified by using the mean square error bound criterion and L-infinity tracking error bound criterion.

FP12-4 3751
Cascaded synchronization of two pendula

Loria, Antonio Univ. of California at Santa Barbara
Nijmeijer, Hendrik Univ. of Twente
Egeland, Olav Norwegian Univ. of Science & Tech.

We consider two pendula in open loop perturbed by sinusoidals where it is assumed that one can tune the oscillating frequency of one of the two systems. The synchronization goal is then to make the first pendulum to oscillate at the frequency of the second. The controller is a simple linear proportional feedback of the frequency error. The stability proof is based on the key observation that with this linear dynamic extension we can rearrange the “error” dynamics in a cascaded structure. Then we invoke some results on stability analysis of cascaded non-autonomous nonlinear systems in order to prove global uniform asymptotic stability.

FP12-5 3753
A state observer for minimum phase nonlinear systems

Jo, Nam H. Seoul National Univ.
Seo, Jin H. Seoul National Univ.

In this paper a local state observer for minimum phase nonlinear systems is presented. It is shown that if a nonlinear system has asymptotically stable zero dynamics, then there always exists a local state observer for given nonlinear system which guarantees the observation error is less than prescribed bound. It is also shown that if the zero dynamics of given nonlinear system satisfies some proposed condition, then this observer guarantees that the observation error converges to zero. An Illustrative example to show the effectiveness of proposed method is included.

FP12-6 3758
On parameter estimation using level sets

Berg, Jordan M. Texas Tech. Univ.

Consider the problem of selecting the member of a parametrized family of curves that best matches a given curve. This is a key step in determining proper values for adjustable parameters in low-order plasma etching and deposition models. Level set methods offer several attractive features for treating such problems. This paper presents a parameter estimation scheme that exploits the level set formulation. The method is completely geometric; there is no need to introduce an arbitrary coordinate system for the curves.

FP13-1 (I) 3763
Modeling and estimation for a terpolymerization reactor

Amrani, S. H. Telemark College
Haavik, Arve Idar Telemark College
Lie, B. Telemark College
Karjala, Thomas W. Dow Chemical Co.

Because of the limited number of on-line product quality measurements available in polymerization reactors today, there is significant industrial interest in application of on-line modeling and state estimation for process modeling and control. In this paper we investigate model development, observability, and choice of estimation algorithm for a transition-metal-catalyzed, terpolymerization process.

FP13-2 (I) 3768
An adaptive calorimetric measurement strategy for on-line monitoring of conversion in polymerization processes

Fevotte, G. Univ. Claude Bernard Lyon 1

Much research effort has been devoted to the development of sensors capable of providing reliable on-line information about the reaction advancement in polymerization processes. In particular, calorimetric techniques which have been widely investigated in the past, still present real difficulties in multipurpose industrial applications. This paper describes a new strategy for the accurate determination of conversion during batch polymerizations. In addition to the calorimetric data, infrequently-available gravimetric measurements are used to track variations of key-parameters such as the overall heat transfer coefficient. It is shown that accurate estimation of conversion can be obtained, even if unpredictable conversion-dependent and/or batch-to-batch variations are encountered. Batch and semi-batch experiments were performed in a 7-litre bench-scale well-mixed reactor to evaluate the technique. The method has been successfully applied to solution polymerization systems, i.e. Vinyl Acetate/Butyl Acrylate in Ethyl Acetate, and to emulsion copolymerization operations, i.e. Styrene/Butyl Acrylate or Methyl Methacrylate/Vinyl Acetate.

FP13-3 (I) 3773
Monitoring and fault diagnosis of a polymerization reactor by interfacing knowledge-based and multivariate SPM tools

Norvilas, Aras Illinois Inst. of Tech.
Tatara, Eric Illinois Inst. of Tech.
Negiz, Antoine Illinois Inst. of Tech.
DeCicco, Jeffrey Illinois Inst. of Tech.
Cinar, Ali Illinois Inst. of Tech.

An intelligent process monitoring and fault diagnosis environment is developed by interfacing multivariate statistical process monitoring (MSPM) techniques and knowledge-based systems (KBS) for monitoring continuous multivariable process operation. The software is tested by monitoring the performance of a continuous stirred tank reactor for polymerization of vinyl acetate. The real-time KBS G2 and its Diagnostic Assistant (GDA) tool are integrated with MSPM methods based on canonical variate state space (CVSS) process models. Fault detection is based on Hotelling's T2 of state variables and squared prediction errors (SPE) charts. Contribution plots in G2 are used for determining the process variables that have contributed to the out-of-control signal indicated by large T2 and/or SPE values, and GDA is used to diagnose the source cause of the abnormal process behavior. The MSPM modules developed in Matlab are linked with G2 and GDA, permitting the use of MSPM tools for multivariable processes with autocorrelated data. The presentation will focus on the structure and performance of the integrated system. On-line SPM of the multivariable polymerization process is illustrated by simulation studies.

FP13-4 (I) 3778
Nonlinear model predictive control with state estimation in batch polymerization

Berber, Ridvan Univ. of Ankara
Yetik, K. Univ. of Ankara
Calimli, A. Univ. of Ankara

A computationally simple and practical nonlinear control algorithm is developed for temperature control of a batch styrene polymerization reactor. Calculation of control effort is accomplished by a Newton-type single step strategy, combined with a state estimation algorithm. To realize the state estimation, the rigorous system composed of six state variables is divided into subsystems and two extended Kalman filters (EKF) with reduced orders are used for every subsystem. The control and estimation algorithm is implemented in an interactive

real-time data logging, monitoring and control environment through a graphical user interface. Simulation runs revealed good set point tracking during the isothermal stage of the batch operation.

FP13-5 (I) 3865

Study on the estimation and control of a liquid composite molding process

Sourlas, Dennis D. — Univ. of Missouri-Rolla
Naha, Susmito — Univ. of Missouri-Rolla
Patterson, Gary — Univ. of Missouri-Rolla
Parnas, Richard — National Inst. of Standards & Tech.

An on-line nonlinear receding horizon control algorithm is employed in order to achieve setpoint tracking targets in the context of liquid composite molding processes. The robustness of this control strategy against process-model deviations is tested. Finally, recursive parameter estimation is employed as a means of actively enhancing the performance of the process control algorithm.

FP13-6 (I) 3783

A comparative investigation on the heat-release estimation methods for temperature control of a batch polymerization reactor

Nik-Azar, M. — Amir Kabir Univ. of Tech.
Hormozi, F. — Azad Univ.
Parvazi-Nia, M. — Polymer Research Center of Iran

In a batch reactor for the Methyl Methacrylate polymerization (MMA), temperature control was studied. Three methods of Heat-Release Estimation (HRE), namely, Kinetic Model (KM), On-Line Energy Balance (OLEB) and Calorimetric-State Estimator (CSE) were investigated. The following three criteria were used to assess these methods: ability to adjust kinetic errors; ability to adjust against dynamic errors; sensitivity to temperature noises. The results indicate that the CSE method has a better performance with respect to kinetic and dynamic errors. Additionally, by using this method, the temperature control design becomes self-tuning.

FP14-1 3788

Speed sensorless observer for an induction machine with separate bias estimation

Pappano, Vincenzo — New Jersey Inst. of Tech.
Friedland, Bernard — New Jersey Inst. of Tech.

A two-stage observer, for separate state and parameter estimation, based on the State Dependent Riccati Equation filter methodology, is applied to the sixth order model of an induction machine.

FP14-2 3791

A reduced order time-delay control for highly simplified brushless DC motor

Chang, Pyung H. — Korea Adv. Inst. of Sci. & Tech.
Lee, Jung H. — Missile Actuation System Div., ADD
Park, Suk H. — Korea Adv. Inst. of Sci. & Tech.

A reduced-order Time Delay Control (RTDC) has been derived and applied to the position control of a brushless DC motor (BLDCM) with a highly simplified hardware configuration: use of six-step commutation without current control unit. In addition, the closed-loop stability has been analyzed by using the singular perturbation method. Throughout simulation and experimental studies, RTDC has been observed to achieve a performance level approaching to that of a BLDCM adopting sinusoidal commutation with current control unit. More specifically, it has been observed that RTDC effectively compensates for parameter variations, nonlinearities, and the torque ripple caused by six-step commutation, which a conventional PID control cannot handle with adequate performances. This result shows that RTDC enables an economical design without compromising performance. More importantly, the example establishes a case that: a good control method can compensate for the hardware deficiency in a given plant; and as a result it even enables a simpler design of plants at the design stage.

FP14-3 3796

Designing a passivity-based controller for the boost converter using bond graphs

Garcia-Gomez, Janette — Univ. Simon Bolivar
Rimaux, Stephane — A.D.E.R.S.A.
Delgado, Marisol — Univ. Simon Bolivar

The bond graph approach is proposed to obtain a passivity-based controller for the stabilization of the average bond graph model of the boost converter. A damping injection is introduced in order to achieve asymptotic stability. The performance of the proposed controller obtained from the passivity-based model is tested through computer simulation.

FP14-4 3798

On the robust control of synchronous generators

Lahdhiri, Tarek — Univ. of Windsor
Alouani, Ali T. — Tennessee Tech. Univ.

The objective of this paper is to design robust nonlinear excitation controllers for synchronous generators. Since disturbances acting on power systems are of random nature and since the variations of the network parameters can not be known with certainties such systems have to be treated as nonlinear uncertain stochastic systems. To take advantage of well developed linear robust control techniques, differential geometry and stochastic calculus are used to transform the nonlinear system to an equivalent linear system. Simulation results of a single machine infinite-bus system indicate that the proposed control approach is of potential benefits in reaching the desired system performance.

FP14-5 3891

Multilevel linguistic equation controller applied to a 1 MW solar power plant

Juuso, E. K. — Univ. of Oulu
Balsa, P. — Plataforma Solar de Almeria
Valenzuela, L. — Plataforma Solar de Almeria

This paper presents new results of a Multilevel Linguistic Equation Controller to maintain the outlet oil temperature in a 1 MWt Solar Power Plant. The Multilevel Linguistic Equation Controller combines smoothly various control strategies into a compact single controller which can be tuned in a modular way. The operation is very robust in difficult conditions: startup and set point tracking are fast and accurate in variable radiation conditions; the controller can handle efficiently even multiple disturbances.

FP14-6 3803

Modern robust control of a CSI-fed induction motor drive system

Mohamed, Abdelfatah M. — Assiut Univ.

The current source inverter (CSI)-fed induction motor (IM) drive system is an open loop stable system, however due to model uncertainties and operation at different operating points the system exhibits poor performance and may loose stability. This paper utilizes the H-inf Loop Shaping Design Procedure (LSDP) with mu-analysis (mu-LSDP) to design a controller for a CSI-fed induction motor drive system in order to achieve robust stability and robust performance against various model uncertainties. First, the nonlinear dynamic equations of the CSI-fed IM are described in state space form, with emphasis on modeling errors (uncertainties), physical disturbances and noises, then these equations are linearized around an operating point. Second, the H-inf LSDP with mu-analysis procedure is explained. Third, the H-inf LSDP problem formulation is presented with emphasis on the selection of the frequency shaping functions which reflects the robust stability and performance goals. Finally, the mu-LSDP is applied to the controller design of an example system, and numerous simulation results are presented. The results showed that both robust stability and robust performance are achieved.

FP15-1 3809

Blast furnace stove control

Muske, Kenneth R. — Villanova Univ.
Hansen, Glen — Los Alamos National Lab.
Howse, James — Los Alamos National Lab.

Cagliostro, Dominic — Los Alamos National Lab.
Chaubal, Pinakin — Inland Steel Industries, Inc.

This paper outlines the process model and model-based control techniques implemented on the hot blast stoves for the No. 7 Blast Furnace at the Inland Steel facility in East Chicago, Indiana. A detailed heat transfer model of the stoves is developed. It is then used as part of a predictive control scheme to determine the minimum amount of fuel necessary to achieve the blast air requirements. The controller also considers maximum and minimum temperature constraints within the stove.

FP15-2 3811

On the reheat furnace control problem

Pedersen, Lars Malcolm — The Danish Steel Works Ltd.
Wittenmark, Bjorn — Lund Inst. of Tech.

The purpose of this paper is to develop a model and a control algorithm for the slab temperature control problem which is the control of the temperature of a number of steel blocks (slabs) passing through a furnace burner zone. The slab temperature is controlled by varying the zone temperature. A model for a single slab passing through the furnace is developed and the parameters of this model are estimated. Data from reheat furnace no. 2 at The Danish Steel Work Ltd. are used for the identification. The single slab model is used for building a model for all slabs in a burner zone. A slab temperature reference function (heating curve) is found from the slab temperature model. A nonlinear controller is designed to minimize the deviation from this heating curve. The stability and controllability of the system is analyzed in the final part of the paper.

FP15-3 3816

Experimental control of a cupola furnace

Moore, Kevin L. — Idaho State Univ.
Abdelrahman, Mohamed A. — Tennessee Tech. Univ.
Larsen, Eric — Lockheed Martin Idaho Tech. Co.
Clark, Denis — Lockheed Martin Idaho Tech. Co.
King, Paul — U.S. Department of Energy

In this paper we present some final results from a research project focused on introducing automatic control to the operation of cupola iron furnaces. The main aim of this research is to improve the operational efficiency and performance of the cupola furnace, an important foundry process used to melt iron. Previous papers have described the development of appropriate control system architectures for the cupola. In this paper experimental data is used to calibrate the model, which is taken as a first-order multivariable system with time delay. Then relative gain analysis is used to select loop pairings to be used in a multiloop controller. The resulting controller pairs meltrate with blast volume, iron temperature with oxygen addition, and carbon composition with metal-to-coke ratio. Special (nonlinear) filters are used to compute meltrate from actual scale readings of the amount of iron produced and to smooth the temperature measurement. The temperature and meltrate loops use single-loop PI control. The composition loop uses a Smith predictor to discount the deadtime associated with mass transport through the furnace. Experiments conducted at the Department of Energy Albany Research Center’s experimental research cupola validate the conceptual controller design and provide proof-of-concept of the idea of controlling a foundry cupola.

FP15-4 3822

Multi-dimensional size control in rod bar rolling and cold strip rolling by using fuzzy method

Ogai, Harutoshi — Nippon Steel Corp.
Fujii, Akira — Nippon Steel Corp.
Baba, Kanji — Nippon Steel Corp.
Kakimoto, Sumitada — Nippon Steel Corp.
Harakawa, Tetumi — Nippon Steel Corp.

This paper will present a set-up method of roll revolution speed for free tension in Rod Bar Mill and a set-up method of tapered work roll shift in Cold Strip Mill. We discovered that the tension state is detected by the change of load parameter of rod bar rolling mill when end of a bar paths through the roll. The roll revolution speed in next bar is required by fuzzy inference. The fuzzy inference also adjusts control gains based on the stability of the load parameter avoiding the miss operation. In the latter ,we set up the tapered work roll shift in each cold strip mill by fuzzy mathematical programming method. We set the target value of controlled variable, edge drop value, as range by using fuzzy variable. And the tapered work roll shift values are set up by fuzzy maximizing decision method. By this fuzzy method we realized a stable and optimum set-up system.

FP15-5 3824

A real-time expert system with GPC for cold strip mill

Xue, Anke — Zhejiang Univ.
Sun, You-Xian — Zhejiang Univ.

In this paper, a real-time expert system (RTES) for cold strip mill is developed using a generalized predictive control (GPC) approach. A simple model of the cold strip mill for gauge and shape regulation is derived. The expert system captures such an engineer's knowledge for gauge and shape regulation and builds a knowledge base which contains both structural and behavioral knowledge. For the sake of real time control, a rule-based regulator is proposed in the paper. Simulation results are given in the paper to show the good performance of the system designed by the proposed method.

FP15-6 3828

A new method of flatness control in cold rolling process

Qiao, Jun-Fei — Northeastern Univ.
Guo, Ge — Northeastern Univ.
Chai, Tianyou — Northeastern Univ.
Shao, Cheng — Northeastern Univ.

According to practical rolling condition and the requirement of shape control, an adaptive global flatness control system is designed to realize automatic shape control of strip. The setpoint can be provided automatically for each actuator by a set-up model, and the adjustment of each actuator is obtained using fuzzy recognition method. Then the self-tuning controller with pole placement is used for the hydraulic system of a rolling mill. The control system is shown to be successful by the simulation experiments.

FP16-1 (I) 3833

Contour tracking of machine tool feed drive systems

Chiu, George T.-C. — Purdue Univ.

This paper summarizes the current advancement in contour tracking control of machine tool feed drive systems. Contouring performance can be improved by introducing trajectory dependent coupling effect among the feed drive axes. We will summarize various approaches to synthesize these trajectory dependent cross-coupling controllers. Recent advancement in synthesizing linear parameter varying (LPV) controllers provided a good framework for designing trajectory dependent cross-coupling controllers. By transforming the machine tool feed drive dynamics to a local task-based coordinate frame, contour tracking controller can be designed using gain scheduling approach for LPV systems.

FP16-2 (I) 3838

Passive control of bilateral teleoperated manipulators

Li, Perry Y. — Univ. of Minnesota

The control of a bilateral teleoperated manipulator system is considered. The goal of the control are to i) coordinate the motions of the two manipulators according to a predefined kinematic scaling, ii) render the dynamics of a locked system, and its response to forces from the human operator and environment to approximate that of predefined natural dynamics, iii) to provide for possible scaling of power. In addition, for safety reasons, the closed loop system need to remain passive. For linear dynamically similar systems, dynamics of the system can be block diagonalized into two decoupled mechanical systems: the shape system that deals with the coordination error, and the locked system that describe the average motion of the two manipulators. The passive velocity field control methodology is then applied to the shape system to regulate the

coordination error at 0 and at the same time preserves the passivity of the overall system.

FP16-3 (I) 3843
A general framework of coordinated motion control subjected to actuator saturation
Niu, Weiguang Univ. of California at Berkeley
Tomizuka, Masayoshi Univ. of California at Berkeley

In this paper, a general framework of motion coordination of two axes system in the presence of actuator saturation is proposed. The framework includes three parts: feedback controller, feedforward controller and on-line trajectory planner. The feedback controller is designed using an anti-windup design to reduce the degradation in performance of each axis. The discrete time zero phase error tracking controller (ZPETC) is used as a feedforward controller. The on-line trajectory planner is for maintaining the contouring accuracy by assuring not to saturate either of the X-axis and Y-axis actuator. The desired outputs for X- and Y-axis are given as sequences of points. When the actuator of any axis is predicted to saturate, more points are inserted in the original sequence to slow down the motion. The effectiveness of the proposed framework is studied by simulation of a two-axis Cartesian positioning system.

FP16-4 (I) 3848
Analysis and control of a class of large-scale interconnected nonlinear systems
Pagilla, Prabhakar R. Oklahoma State Univ.

In this paper, decentralized controller design and stability analysis of a class of large-scale interconnected nonlinear systems is presented. Each subsystem in the overall system is nonlinear and so are the interconnections that join the subsystems. For controller synthesis the interconnecting nonlinear functions are known to satisfy a bound which is a polynomial in the states. The nonlinear interconnections need not satisfy any symmetry property. We show global exponential stability of the closed-loop interconnected system for the proposed decentralized controller. Robustness of the decentralized controller to a class of interconnections that do not satisfy matching conditions is also shown.

FP16-5 (I) 3853
Stick-slip operation of the modular distributed manipulator system
Luntz, Jonathan Carnegie Mellon Univ.
Messner, William C. Carnegie Mellon Univ.
Choset, Howie Carnegie Mellon Univ.

The Modular Distributed Manipulator System (MDMS) is a novel materials handling system which is a fixed array of actuated wheels capable of inducing arbitrary motions in the plane. The wheels transport and manipulate objects (parcels) that rest on the array. Each wheel applies a force to the parcel through a friction contact. The motion of the parcel is determined by a combination of parcel weight distribution, wheel and motor dynamics, wheel reference speeds, and friction. This work focuses on a stick-slip friction model and its impact on the dynamics of a parcel on the array. Factors such as coefficient of friction and parcel size and weight determine which wheels slide and which wheels roll. Ranges of parameters are determined which provide complete rolling and complete sliding contact. Simulations are performed to demonstrate the dynamics of the parcel.

FP16-6 (I) *
Discussion
Li, Perry Y. Univ. of Minnesota