Scanning the Issue

A Moving Horizon Optimization Approach to Networked Control System Design, *Goodwin, Haimovich, Quevedo, and Welsh.*

This paper presents a control system design strategy for multivariable plants where the controller, sensors, and actuators are connected via a digital, data-rate limited, communications channel. In order to minimize bandwidth utilization, a communication constraint is imposed which restricts all transmitted data to belong to a finite set and only permits one plant to be addressed at a time. The problem is addressed using "moving horizon" techniques, and the results are tested in an experimental setup involving the control of fluid levels in several tanks. Communications between the controller and plant are over the IEEE 802.3 standard Ethernet, 10Base-T configuration utilizing the TCP/IP protocol.

Distributed Control of Systems Over Discrete Groups, *Recht and D'Andrea.*

This paper discusses distributed controller design and analysis for distributed systems with arbitrary discrete-symmetry groups. It is shown how recent results for designing control systems for spatially interconnected systems, based on semidefinite programming, are applicable to a much larger class of interconnection topologies. It is also shown how to exploit the form of the symmetry group to produce a hierarchy of decreasingly conservative analysis and synthesis conditions.

Kalman Filtering With Intermittent Observations, *Sinopoli, Schenato, Franceschetti, Poolla, Jordan, and Sastry.*

The paper considers the problem of performing Kalman filtering with intermittent observations. When data travel along unreliable communication channels in a large, wireless, multihop sensor network, the effect of communication delays and loss of information in the control loop cannot be neglected. The problem is addressed starting with a discrete Kalman filtering formulation, and modeling the arrival of the observations as a random process. Statistical convergence properties of the estimation error covariance are developed, showing the existence of a critical value for the arrival rate of the observations, beyond which a transition to an unbounded state error covariance occurs. An upper and lower bound on this expected state error covariance is given.

Information Flow and Cooperative Control of Vehicle Formations, *Fax and Murray.*

This paper treats the problem of cooperation among a collection of vehicles performing a shared task using intervehicle communication to coordinate their actions. Using the methods of graph theory, a relationship is established between formation stability and the topology of the communication network. A Nyquist criterion is given that uses the eigenvalues of the graph Laplacian matrix to determine the effect of the graph on formation stability. This paper also studies decentralized information exchange between vehicles. A separation principle is proved, showing that formation stability is achieved if the information flow is stable for the given graph and if the local controller stabilizes the vehicle. The information flow can be rendered highly robust to changes in the graph, thus enabling tight formation control despite limitations in intervehicle communication capability.

When Bode Meets Shannon: Control-Oriented Feedback Communication Schemes, *Elia.*

In this paper, a general equivalence is established between the problem of feedback stabilization through an analog communication channel and a feedback communication strategy which is a generalization of Schalkwijk and Kailath. It is shown that the achievable transmission rate of the strategy is given by the Bode's Sensitivity integral formula. The results of this paper allow the use of many results and design tools from control theory for the design of feedback communication schemes providing desired communication rates. The results also provide lower bounds on the channel feedback capacity. The paper considers single user gaussian channels with memory, and memoryless multiuser broadcast, multiple access, and interference channels. In all cases, and under an average transmission power constraint, the results either achieve the feedback capacity (when this is known), recover known best rates, or provide new best achievable rates.

Decentralized Control of Discrete-Event Systems With Bounded or Unbounded Delay Communication, *Tripakis.*

This paper introduces problems of decentralized control with delayed communication, where delays are either unbounded or bounded by a given constant k. In the k-bounded delay model, during the time between the transmission of a message and its receipt, the plant can execute at most k events. In the unbounded delay model, the plant can execute any number of events between message transmission and receipt of the message. It is shown that the framework yields an infinite hierarchy of control problems, where the hierarchy is the result of the property that controllers which work in a given network will also work in a less nondeterministic network. Checking the existence of controllers in the unbounded-delay case or in the case without communication are undecidable problems. A related decentralized observation problem with bounded delay communication is, however, decidable.

Distributed Control Design for Systems Interconnected Over an Arbitrary Graph, *Langbort, Chandra, and D'Andrea.*

This paper treats the problem of synthesizing a distributed output feedback controller achieving $\mathcal{H}_\infty$ performance for a system composed of different interconnected sub-units, when the topology of the underlying graph is arbitrary. This paper provides sufficient conditions in the form of finite-dimensional linear matrix inequalities when the interconnections are assumed to be ideal. These inequalities are coupled in a way that reflects the spatial structure of the problem and reduce to recently proven results in the case of spatial invariance and/or nearest neighbor coupling. The case of lossy interconnection links is treated and results are presented for systems whose interconnection relations can be captured by a class of integral quadratic constraints that includes constant delays.

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Consensus Problems in Networks of Agents With Switching Topology and Time-Delays, *Olfati-Saber and Murray.*

This paper discusses consensus problems for networks of dynamic agents with fixed and switching topologies. The authors analyze three cases: i) directed networks with fixed topology, ii) directed networks with switching topology, and iii) undirected networks with communication time-delays and fixed topology. It introduces two consensus protocols for networks with and without time-delays and provides a convergence analysis in all three cases. It establishes a direct connection between the algebraic connectivity (or Fiedler eigenvalue) of the network and the performance (or negotiation speed) of a linear consensus protocol.

Quantized Stabilization of Linear Systems: Complexity Versus Performance, *Fagnani and Zampieri.*

This paper analyzes the stabilization problem for discrete-time linear systems with multidimensional state and one-dimensional input using quantized feedback with a memory structure, focusing on the tradeoff between complexity and performance. A quantized controller with memory is a dynamical system with a state–space, a state updating map and an output map. The quantized controller complexity is in terms of three indices. The first index L coincides with the number of the controller states. The second index is the number M of the possible values that the state updating map of the controller can take at each time. The third index is the number N of the possible values that the output map of the controller can take at each time. The index N corresponds also to the number of the possible control values that the controller can choose at each time. The performance index is chosen to be the time T needed to shrink the state of the plant from a starting set to a target set. The contraction rate C, namely the ratio between the volumes of the starting and target sets, is introduced. The relations between these parameters for various quantized stabilizers are discussed, and a number of results showing the intrinsic limitations of the quantized control are given. In particular, it is shown that in order to obtain a control strategy which yields arbitrarily small values of $T \in C$ (a requirement which can be interpreted as a weak form of the pole assignability property), it is necessary that $LN \in C$ is large enough.

Stochastic Linear Control Over a Communication Channel, *Tatikonda, Sahai, and Mitter.*

This paper treats linear stochastic control systems when there is a communication channel connecting the sensor to the controller. The problem consists of designing the channel encoder and decoder as well as the controller to satisfy some given control objectives. The research being reported examines the role communication has on the classical LQG problem. Conditions are given under which the classical separation property between estimation and control holds and the certainty equivalent control law is optimal. Bounds are obtained on the achievable performance, and the inherent tradeoffs between control and communication costs are described. It is shown that optimal quadratic cost decomposes into two terms: A full knowledge cost and a sequential rate distortion cost.

Stability of Model-Based Networked Control Systems With Time-Varying Transmission Times, *Montestruque and Antsaklis.*

In model-based networked control systems (MB-NCSs) an explicit model of the plant is used to produce an estimate of the plant behavior between feedback transmission times. In this paper, the stability of MB-NCSs is studied when the controller/actuator is updated with the sensor feedback data at nonconstant time intervals. For networked control systems with transmission times that are time varying within a time interval, sufficient conditions for Lyapunov stability are derived. For systems with transmission times driven by stochastic processes with identically independently distributed or Markov-chain transmission times, sufficient conditions for almost sure stability as well as mean square stability are presented.

Robust Quantization for Digital Finite Communication Bandwidth (DFCB) Control, *Li and Baillieul.*

The problem of DFCB control has come to the attention of the research community in connection with a growing interest in the development of distributed and/or networked control systems. In these systems, actuators, sensors, and other components are connected via data-rate constrained links such as wireless radio, etc. This paper studies a scalar model of DFCB control that accomodates time-varying data-rate constraints, such as might occur with intermittent network congestion, and asynchronism of sampling and control actuation. Because of the possibly unpredictable fluctuation of the data-rate, there is interest in feedback control designs that will tolerate significantly constrained data rates on feedback loops, while providing acceptable performance when such data-rate constraints are not in force. In light of a very basic notion of acceptable performance, it is shown that control designs with different number of quantization levels tolerate constrained data-rates differently. This leads to the conclusion that binary control represents the most robust control quantization under data-rate constraints imposed by time-varying congestion on the feedback communication channel. The advantage margin of binary control is further investigated numerically with and without the sampling-control asynchronism being considered. It is shown that the advantage margin is more substantial when the sampling-control asynchronism is significant. A design of quantized (binary) feedback with side channel information is proposed, and stability properties are discussed. The paper concludes by examining performance limitations of binary coding in the presence of noise.

Topological Feedback Entropy and Nonlinear Stabilization, *Nair, Evans, Mareels, and Moran.*

It is well-known in the field of dynamical systems that entropy can be defined rigorously for completely deterministic open-loop systems. However, such definitions have found limited application in engineering, unlike Shannon's statistical entropy. In this paper, it is shown that the problem of communication-limited stabilization is related to the concept of topological entropy, introduced by Adler *et al.* as a measure of the information rate of a continuous map on a compact topological space. Using similar open cover techniques, the notion of topological feedback entropy (TFE) is defined in this paper and proposed as a measure of the inherent rate at which a map on a noncompact topological space with inputs generates stability information. It is then proven that a topological dynamical plant can be stabilized into a compact set if and only if the data rate in the feedback loop exceeds the TFE of the plant on the set. By taking appropriate limits in a metric space, the concept of local TFE (LTFE) is defined at fixed points of the plant, and it is shown that the plant is locally uniformly asymptotically stabilizable to a fixed point if and only if the data rate exceeds the plant LTFE at the fixed point. For continuously differentiable plants in Euclidean space, real Jordan forms and volume partitioning arguments are then used to demonstrate that LTFE is the sum of the base-2 algorithms of the unstable eigenvalues of the Jacobian at the fixed point.

Scalar Estimation and Control With Noisy Binary Observations, *Simsek, Jain, and Varaiya.*

This note considers a simple one-dimensional unstable system whose observations are sent to a state estimator over a noisy binary communication link. The problem is to design an encoding scheme and a decoder, such that the estimation error is stable. A novel, simple, but efficient estimator for the binary symmetric channel (BSC) is constructed, and the results are compared with the nonconstructive bounds of Sahai.