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14. ABSTRACT
The research developed in this grant lead to a significant body of interrelated results that are relevant for the design and analysis of performance of networked control systems. These results may have an impact on the design and provable performance certification of networks of semi-autonomous systems that are required to execute safety critical missions with high precision in the presence of communication constraints.

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NETWORKED GUIDANCE AND CONTROL FOR MOBILE MULTI-AGENT SYSTEMS: A MULTI-TERMINAL (NETWORK) INFORMATION THEORETIC APPROACH

Final Report

FA95500810120
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1- Main results

The following is an abridged list of the main achievements that resulted from research supported by this grant:

- In collaboration with Dr. V. Gupta (UND), we were the first to characterize the necessary and sufficient conditions for stabilization in a networked control framework where there is a channel between the controller and the actuator.

- Under my supervision, Mr. Kenneth Running has solved the problem of optimal tracking for Markovian Jump Linear Systems. This can be applied to networked control systems whose interconnecting links feature random erasures.

- In collaboration with Dr. J. Goncalves (U. Cambridge, UK), we have developed a new method to design and analyze master equations, which are a mainstay model for large-scale systems and biological networks.

- In collaboration with Drs. V. Gupta and John Baras (UMD), we have solved the problem of optimal sensor allocation for control in the presence of noise and communication constraints.

- In collaboration with Tsachy Weissman (Stanford U.), we have developed a framework and new performance analysis methodology for control-inspired communication schemes for Gaussian channels in the presence of quantized feedback.

- Under my supervision, Mr. Gabriel Lipsa identified a new class of team decision problems that extends Witsenhausen's original example. Mr. Lipsa also proposed and analyzed the performance of new methods for the optimal design of such a new class of systems.

- Under my supervision, Mr. Lipsa solved the long standing problem of designing jointly optimal transmitters and receivers for distributed state estimation in the presence of communication costs.

2- Journal Publications

G. Lipsa and N. C. Martins, “Optimal memoryless control in Gaussian noise: A simple counterexample,” Volume 47, Issue 3, March 2011, Pages 552–558

In this paper, we investigate control strategies for a scalar, one-step delay system in discrete-time, i.e., the state of the system is the input delayed by one time unit. In contrast with classical approaches, here the control action must be a memoryless function of the output of the plant, which comprises the current state corrupted by measurement noise. We adopt a first order state-space representation for the delay system, where the initial state is a Gaussian random variable. In addition, we assume that the measurement noise is drawn from a white and Gaussian process with zero mean and constant variance. Performance evaluation is carried out via a finite-time quadratic cost that combines the second moment of the control signal, and the second moment of the difference between the initial state and the state at the final time. We show that if the time-horizon is one or two then the optimal control is a linear function of the plant’s output, while for a sufficiently large horizon a control taking on only two values will outperform the optimal affine solution. This paper complements the well-known counterexample by Hans Witsenhausen, which showed that the solution to a linear, quadratic and Gaussian optimal control paradigm might be nonlinear. Witsenhausen’s counterexample considered an optimization horizon with two time-steps (two stage control). In contrast with Witsenhausen’s work, the solution to our counterexample is linear for one and two stages but it becomes nonlinear as the number of stages is increased. The fact that our paradigm leads to nonlinear solutions, in the multi-stage case, could not be predicted from prior results. In contrast to prior work, the validity of our counterexample is based on analytical proof methods. Our proof technique rests on a simple nonlinear strategy that is useful in its own right, since it outperforms any affine solution.

G. Lipsa and N. C. Martins, “Remote State Estimation With Communication Costs for First-Order LTI Systems,” IEEE Transactions on Automatic Control, Vol. 56, No. 9, September 2011, Pages 2013-2025

Consider a first order linear time-invariant discrete time system driven by process noise, a pre-processor that accepts causal measurements of the state of the system, and a state esti- mator. The pre-processor and the state estimator are not co-lo- cated, and, at every time-step, the pre-processor transmits either a real number or a free symbol to the estimator. We seek the pre-pro- cessor and the estimator that jointly minimize a cost that com- bines two terms; the expected squared state estimation error and a communication cost. In our formulation, the transmission of a real number from the pre-processor to the estimator incurs a positive cost while free symbols induce zero cost. This paper proves analyt- ically that a symmetric threshold policy at the pre-processor and a Kalman-like filter at the estimator, which updates its estimate lin- early in the presence of free symbols, are jointly optimal for our problem.

V. Gupta and N. C. Martins, “On Stability in the Presence of Analog Erasure Channel Between the Controller and the Actuator,” IEEE Transactions on Automatic Control, Vol. 55, No. 1, January 2010, Pages 175-179

Consider a discrete-time networked control system, in which the controller has direct access to noisy measurements of the output of the plant. However, information flows from the controller to the actuator via a channel that features Bernoulli erasure events. If an erasure occurs, the channel outputs an erasure symbol; otherwise, it transmits a real finite-dimensional vector. We determine necessary and sufficient conditions for the stabilizability of an unstable linear time-invariant finite-dimensional plant. Given a minimal state-space representation for the plant, the necessary and sufficient conditions for stabilizability are expressed in terms of the probability of erasure at the channel and of the spectral radius of the one-step state transition matrix. There are two main results in the technical note. The first result shows that if the actuator has processing capabilities, then the necessary and sufficient conditions for stabilizability remain unchanged with or without acknowledgements from the actuator to the controller. The second result shows that the stabilizability conditions are identical for two types of actuators: (Type I) Processing at the actuator has access to the plant's model; (Type II) Processing at the actuator uses a universal algorithm that does not depend on the model of the plant. Thus, neither the knowledge of the model of the plant at the actuator, nor the presence of acknowledgements from the actuator to the controller, can be used to alter or relax the necessary and sufficient conditions for stabilizability.

V. Gupta and N. C. Martins, “Optimal tracking control across erasure communication links, in the presence of preview,” Issue 16, Vol 19, Control under limited information: Special issue (Part I), November 2009, Pages: 1837-1850

Consider two identical discrete-time, finite-dimensional, linear and time-invariant systems denoted as leader and follower. The leader system is driven by a deterministic control input and by a zero-mean white Gaussian process noise. In this paper, we address the problem of designing a networked control scheme for the follower system that guarantees that the state of the follower system tracks the state of the leader system optimally, according to a mean squared cost. We adopt a networked control scheme featuring two erasure links and three design blocks: a controller acting on the follower system and two encoders, one at the output of each system. The controller has remote access to noisy measurements of the state of both systems, via two erasure links that are used to connect each encoder to the controller. We consider erasure links whose erasure events occur according to a Bernoulli process. If an erasure occurs then no information is transmitted, otherwise a finite vector of real numbers is conveyed through the link. The purpose of the encoders is to process noisy measurements of the output of each system prior to transmission over the corresponding erasure link. While the encoder of the follower system has access to current measurements, the encoder of the leader system has access to measurements that are advanced in time by a finite time interval (also denoted as preview). This paper describes a methodology for the design of controller and encoders that are jointly optimal, with respect to optimal tracking of the leader system by the follower system. We also obtain explicit necessary and sufficient conditions for the existence of a scheme that guarantees that the tracking error has finite second moment.

N. C. Martins and J. M. Goncalves, "A Linear Programming Approach to Parameter Fitting for the Master Equation," IEEE Transactions on Automatic Control, Vol 54, Issue 10, October, 2009, Pages: 2451 – 2455

This technical note proposes a new framework for the design of continuous time, finite state space Markov processes. In particular, we propose a paradigm for selecting an optimal matrix within a pre-specified pencil of transition rate matrices. Given any transition rate matrix specifying the time-evolution of the Markov process, we propose a class of figures of merit that upper-bounds the long-term evolution of any statistical moment. We show that optimization with respect to the aforementioned class of cost functions is tractable via dualization and linear programming methods. In addition, we suggest how this approach can be used as a tool for the sub-optimal design of the master equation, with performance guarantees. Our results are applied to illustrative examples.

K. D. Running and N. C. Martins, "Optimal Preview Control of Markovian Jump Linear Systems," IEEE Transactions on Automatic Control, Volume 54, Issue 9, Sept. 2009 Page(s): 2260 – 2266

In this technical note, we investigate the design of controllers, for discrete-time Markovian jump linear systems, that achieve optimal reference tracking in the presence of preview (reference look-ahead). For a quadratic cost and given a reference sequence, we obtain the optimal solution for the full information case. The optimal control policy consists of the additive contribution of two terms: a feedforward term and a feedback term. We show that the feedback term is identical to the standard optimal linear quadratic regulator for Markovian jump linear systems. We provide explicit formulas for computing the feedforward term, including an analysis of convergence**.**

Vijay Gupta, Nuno C. Martins and John S. Baras, "Optimal Output Feedback Control Using Two Remote Sensors Over Erasure Channels," IEEE Transactions on Automatic Control, Volume 54, Issue7, July 2009 Page(s): 1463 – 1476

Consider a discrete-time, linear time-invariant process, two sensors and one controller. The process state is observed in the presence of noise by the sensors, which are connected to the controller via links that feature erasure. If a link transmits successfully then a finite-dimensional vector of real numbers is conveyed from the sensor to the controller. If an erasure event occurs, then any information conveyed over the link is lost. This paper addresses the problem of designing the maps that specify the processing at the controller and at the sensors to minimize a quadratic cost function. When the information is lost over the links either in an independent and identically distributed (i.i.d.) or in a (time-homogeneous) Markovian fashion, we derive necessary and sufficient conditions for the existence of maps such that the process is stabilized in the bounded second moment sense. We also solve the optimal design problem in the presence of delayed noiseless acknowledgment signals at the sensors from the controller for an arbitrary packet drop pattern. We provide explicit recursive schemes to implement our solution. We also indicate how our approach can be extended to situations when more than two sensors are available and when the sensors can cooperate. The analysis also carries over to the case when each point-to-point erasure link connecting the sensors and the controller is replaced by a network of erasure links.

Nuno C. Martins and Tsachy Weissman, "Coding for Additive White Noise Channels With Feedback Corrupted by Quantization or Bounded Noise," IEEE Transactions on Information Theory, Volume 54, Issue 9, Sept. 2008 Page(s): 4274 - 4282

We present coding strategies, which are variants of the Schalkwijk-Kailath scheme, for communicating reliably over additive white noise channels in the presence of corrupted feedback. Our framework comprises an additive white forward channel and a feedback link. We consider two types of corruption mechanisms in the feedback link. The first is quantization noise, i.e., the encoder receives the quantized values of the past outputs of the forward channel. The quantization is uniform, memoryless and time invariant. The second corruption mechanism is an arbitrarily distributed additive bounded noise. Here we allow symbol-by-symbol encoding at the input to the feedback link. We propose explicit schemes featuring positive information rate and positive error exponent. If the forward channel is additive white Gaussian (AWGN) then, as the amplitude of the noise at the feedback link decreases to zero, the rate of our schemes converges to the capacity of the channel. Moreover, the probability of error is shown to converge to zero at a doubly exponential rate. If the forward channel is AWGN and the feedback link consists of an additive bounded noise channel, with signal-to-noise ratio (SNR) constrained symbol-by-symbol encoding, then our schemes achieve rates arbitrarily close to capacity, in the limit of high SNR (at the feedback link).

3- Awards

Nuno C. Martins received the 2010 IEEE CSS George Axelby award, the 2010 ISR/UMD Outstanding Systems Engineering Faculty award and the 2010 ECE/UMD George Corcoran award for Teaching Excellence.

Nuno C. Martins was also promoted in June 2011 to the rank of Associate Professor of Electrical and Computer Engineering with tenure.

4- Personnel Supported During this Grant

Besides the PI, this grant was a major source of support to Dr. Gabriel Lipsa who concluded his Ph.D. Thesis in 2010 under the PI's supervision. Dr. Lipsa is currently a researcher (staff) at the IMF, in Washington DC.

5- Invited Talks (During this grant)

- Northrop Grumman, Oceanic, Annapolis, MD, November, 25, 2008 (Host: Randall Smith)

- Air Force Research Laboratory, Wright-Patterson Air Force Base, Beavercreek, OH, February 13, 2009

- University of California, San Diego, at the Cymer Center for Control Systems and Dynamics, May 18, 2009
- University of California at Berkeley, EECS Department, November 6, 2009
- Army Research Laboratory, Adelphi, MD, March 12, 2010
- Air Force Research Laboratory, Wright-Patterson Air Force Base, Beavercreek, OH, March 18, 2010
- Boston University, Center For Information And Systems Engineering, Boston, MA, April 9, 2010
- Yale University, Electrical Engineering Department, New Haven, CT, May 22, 2010

5- Potential Impact on DoD Capabilities

The research developed in this grant lead to a significant body of interrelated results that are relevant for the design and analysis of performance of networked control systems. These results may have an impact on the design and provable performance certification of networks of semi-autonomous systems that are required to execute safety critical missions with high precision in the presence of communication constraints.