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Networked Guidance and Control for Mobile Multi-Agent

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13. SUPPLEMENTARY NOTES
This report was submitted 17 days after the deadline because the PI was on travel.

14. ABSTRACT
This grant sponsored work on fundamental aspects of the following research themes: A-1) We have pioneered the design of optimal event-based remote estimation systems for different types of information constraints. /In particular, we investigated the case when multiple sensor-estimator pairs must share a resource-limited network, and we formulated and solved the case when the communication from sensors to estimators is hindered by collisions. We proposed methods to design optimal remote estimation systems when channels that are subject to energy harvesting mechanisms are used to disseminate information from the sensors to the estimators. A-2) We proposed a new parametrization that allows for the norm-optimal design of decentralized controllers. Our work builds on a coordinate-free method that does not require complicated factorizations and does not need the controller to be stable. B) We used information theoretic methods to obtain a convex program to maximize the number recurrent states of an MDP. This has applications to the design of memoryless policies that maximize the number of targets that can be persistently suveilled by a mobile agent, subject to dynamic constraints on the agent and other restrictions that can be used to model power limitations and safety constraints.

15. SUBJECT TERMS
Distributed Control and Estimation, Information Theoretic Methods

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FINAL REPORT

"Networked Guidance and Control for Mobile Multi-Agent Systems: A Multi-Terminal (Network) Information Theoretic Approach"
AFOSR Grant FA95501110182
Program Manager: Fariba Fahroo, Ph.D.

1. Outline of the work performed and main results: (for more details see the abstracts in Section 3 of this report)

This grant sponsored work on fundamental aspects of the following research themes:

- Analysis and design of optimal distributed estimation and control systems subject to information and resource constraints:

    - *We have pioneered the design of optimal event-based remote estimation systems for different types of information constraints. In [2] we investigate the case when multiple sensor-estimator pairs must share a resource-limited network, while in [7] we formulate and solve the case in which the communication from the sensors to the estimators is hindered by collisions. In [6] we propose methods to design optimal remote estimation systems when channels that are subject to energy harvesting mechanisms are used to disseminate information from the sensors to the estimators.*

    - *In [8] we propose a new parametrization for the norm-optimal design of decentralized controllers. In contrast with prior work, [8] builds on a coordinate-free method that does not require complicated factorizations and does not need the controller to be stable. The thesis [3] addresses aspects of optimal control in the presence of secrecy constraints.*

- Analysis and design of optimal feedback supported on information theoretic principles.

    - In [1], we used information theoretic methods to obtain a convex program to maximize the number of recurrent states of an MDP. This has applications to the design of policies that maximize the number of objects that can be persistently suveilled by a mobile agent [5], subject to dynamic constraints on the agent. Our formulation also allows for constraints on power and safety.

2. Transitions to DoD

In collaboration with ARL and NAVAIR, we are exploring applications of [6] to the design of remote estimation systems that include a human operator. The operator provides additional expert information that is used to improve the performance of the overall system. The main idea is to use the state-dependent channel proposed in [6] to model certain human behaviors, such as bias and workload-related loss of reliability.

3. Publications acknowledging the grant (including abstract when suitable):

[1] ***Eduardo Arvelo and Nuno C. Martins, "Maximizing the set of recurrent states of an MDP subject to convex constraints," Automatica 50 (2014), pp. 994-998***

Abstract:
This paper focuses on the design of time-homogeneous fully observed Markov decision processes (MDPs), with finite state and action spaces. The main objective is to obtain policies that generate the maximal set of recurrent states, subject to convex constraints on the set of invariant probability mass functions. We propose a design method that relies on a finitely parametrized convex program inspired on principles of entropy maximization. A numerical example is provided to illustrate these ideas.

[2] ***Marcos M. Vasconcelos and Nuno C. Martins, "Remote Estimation Games over Shared Networks," Proceedings of the 2014 Allerton Conference on Communication, Control, and Computing*** *(page numbers not yet available)*

Abstract: Consider a system that is formed by two sensors, which measure a random variable each, and two remote estimators. Each estimator is tasked to produce an estimate of one of the variables based on information sent to it by its corresponding sensor. We propose a new class of problems in which information is transmitted from the sensors to the estimators via a collision channel with and without capture. Our results characterize the structure of the policies that are in Nash equilibrium or are secure in a well-defined sense.

[3] ***Waseem Malik, Model Based Optimization And Design Of Secure Systems, Ph.D. Thesis, University of Maryland at College Park, 2013***

[4] ***Aditya Mahajan, Nuno C. Martins, Michael C. Rotkowitz and Serdar Yuksel, "Information Structures in Optimal Decentralized Control," 2012 IEEE CDC, pp. 1291-1306***

Abstract: This paper provides a comprehensive characterization of information structures in team decision problems and their impact on the tractability of team optimization. Solution methods for team decision problems are presented in various settings where the discussion is structured in two foci: The first is centered on solution methods for stochastic teams admitting state-space formulations. The second focus is on norm-optimal control for linear plants under information constraints.

[5] ***Eduardo Arvelo, Eric Kim and Nuno C. Martins, "Maximal Persistent Surveillance under Safety Constraints," ICRA 2013, pp. 4048-4053***

Abstract: This paper presents a method for the design of time-invariant memoryless control policies for robots tasked with persistent surveillance of an area in which there are
forbidden regions. We model each robot as a controlled Markov chain whose state comprises its position on a finite two-dimensional lattice and the direction of motion. The goal is to find the minimum number of robots and an associated time-invariant memoryless control policy that guarantees that the largest number of states is persistently surveilled without ever visiting a forbidden state. We propose a design method that relies on a finitely parametrized convex program inspired by entropy maximization principles. For clarity of exposition, we focus on

simple dynamics and state/control spaces, however the proposed methodology can be extended to more general cases. Numerical examples are provided.

(submitted)

[6] ***David Ward, Nuno C. Martins and Brian M. Sadler, "Optimal Remote Estimation over a Class of Action Dependent Switching Channels," submitted to the 2015 American Control Conference***

Abstract: Consider a remote estimation system formed by a channel and an encoder that assesses a continuous random variable denoted as source. The internal structure of the channel has a finite state machine (FSM) whose state dictates the transmission characteristics. Each state of the FSM corresponds to a discrete memoryless channel (DMC). At each channel use, information is transmitted from the encoder to the channel output according to the DMC selected by the current FSM state. This class of channels is denoted as Action Dependent Switching Channel, or ADS. An action feedback policy maps the channel's output into the input of the FSM. This paper investigates methods to analyze and design an action feedback policy and encoder that minimize the differential entropy of the source conditioned on the channel output. We show that there are optimal action feedback policies for which the input to the FSM is a deterministic sequence that does not depend on the channel output. We also provide additional structural results for the case when the FSM parametrizes a set of Binary Symmetric Channels (BSC) with differing crossover probabilities. Here, we consider that the ADS contains states of no transmission, which are modeled as a BSC crossover probability of one half. In this case, the FSM is also used to model channel degradation as a result of multiple transmissions, and it also allows for recovery when there are no transmissions. Our results show that the optimal encoder and action feedback policies can be computed separately. We also discuss the relevance of this model to applications for which the encoder is powered by an energy harvesting system, and also when the channel represents a human decision maker whose reliability and bias are affected by current and past outputs.

(Working papers to be submitted until the end of 2014)

[7] ***Marcos M. Vasconcelos and Nuno C. Martins, "Optimal Estimation over the Collision Channel: The Static Case," to be submitted to the IEEE Transactions on Automatic Control or Automatica in 2014 – draft available upon request***

Abstract: Consider a system that comprises a remote estimator and two sensors that observe a random variable each. The goal of the remote estimator is to produce estimates of the random variables based on information that is transmitted to it by the sensors. The random variables are independent and information is transferred from the sensors to the estimator via a collision channel. Each sensor has the authority to decide what and whether to transmit, and simultaneous transmissions result in a collision symbol to be received at the estimator. In our formulation, there is no communication between the sensors, which precludes the use of coordinated strategies. Our results characterize the structure of policies at the sensors and the remote estimator that are optimal with respect to an expected mean squared error. We show that, when an optimum exists, there are optimal policies at the sensors that use deterministic threshold strategies to decide when to transmit. In our analysis, we prove that the computation of a person- by-person optimal threshold-based policy can be recast as a one-bit optimal quantization problem for which the cost is non-uniform across representation symbols. We show the existence of such optimal quantizers and we provide an iterative procedure akin to Lloyd-Max algorithm that is guaranteed to converge globally to a locally optimal solution. The iterative method converges to an optimal solution in all numerical examples we have tried, one of which is discussed here. We also present

conditions that guarantee the existence of asymmetric optimal threshold policies even when the overall framework is symmetric, such as when the random variables are Gaussian zero mean with appropriately chosen variances.

[8] Serban Sabau, Nuno C. Martins and Michael C. Rotkowitz, "A convex coordinate-free parameterization subject to SQI subspace constraints," to be submitted to Automatica

Abstract: This paper addresses the design of controllers, subject to given subspace constraints, for finitedimensional linear time-invariant plants. A controller is deemed admissible if it satisfies the constraints. Prior results introduced an algebraic test, denoted as quadratic invariance (QI), that uses the subspace constraints imposed on the controller and the plant to determine the existence of a convex parametrization of all admissible stabilizing controllers. If such a parametrization exists then it can be obtained via Youla's classical method, subject to additional convex conditions on the Youla parameter. Here, we adopt the associated notion of strong quadratic invariance (SQI), which is equivalent to QI in many cases of interest, such when it is used to express sparsity constraints on the controller. Under the assumption that the subspace constraints are SQI, this paper introduces a new parametrization that is not based on Youla's method and yet is convex and also allows norm-based optimal control formulations to be cast as model matching problems. It is based on the so–called coordinate free approach, which was originally developed in a centralized setting, and here is extended to the case in which the controllers are constrained to a SQI subspace. The coordinate free approach parametrizes the closed loop map directly and it relies on the knowledge of an initial admissible stabilizing controller that does not need to be stable. This is in contrast with previous approaches that either require an initial admissible stable stabilizing controller, or are based on Youla's method that requires a doubly–coprime factorization of the plant that must satisfy additional conditions that depend on the constraints.

4. Personnel:

Students partially funded by this grant E. Arvelo, S. Park, D. Ward, M. Vasconcelos, W. Malik.

5. Talks in which AFOSR funding has been acknowledged (2011-2014):

1. Colloquium speaker at CCDC, U. California at Santa Barbara, Santa Barbara, Ca, Sept 23, 2011 (Host: Andrew Teel)

2. Colloquium speaker at the Department of Automatic Control, Lund University, Sweden, October 6, 2011 (Host: Anders Rantzer)

3. Colloquium Speaker for the Seminar Series of the Laboratory for Information and Decision Systems, MIT, October 28, 2012 (Host: Emilio Frazzoli)

4. Colloquium of the Department of Mathematics and Statistics, Queen's University, Canada, March 9, 2012, (Host: Serdar Yuksel)

5. Seminar at Lund University, Sweden, October 18th, 2012 (Host: Bo Bernhardsson)

6. Invited talk at the workshop "Optimal Cooperation, Communication, and Learning in Decentralized Systems," Banff International Research Station for Mathematical Innovation and Discovery, Canada, October 13, 2014

(Upcoming)

1. GRASP seminar series, UPENN, Dec 10th, 2014

2. Mathematisches Forschungsinstitut Oberwolfach Workshop on "Control Theory: A Mathematical Perspective on Cyber-Physical Systems", Feb 22-28, 2015

3. Colloquium of the Electrical Engineering Department at University of Southern California, March 13th, 2015

6. Awards/Distinctions:

N. Martins was selected as a U. Maryland Leadership fellow in 2013