Robust Feedback Control of Reconfigurable Multi-Agent Systems in Uncertain Adversarial Environments

Jeffrey Jacobs
ARIZONA UNIV BOARD OF REGENTS TUCSON

07/09/2015
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA2
Arlington, Virginia 22203
Air Force Materiel Command
REPORT DOCUMENTATION PAGE

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services, Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE
   14-10-2015

2. REPORT TYPE
   Final Performance

3. DATES COVERED
   01-07-2012 to 30-06-2015

4. TITLE AND SUBTITLE
   Robust Feedback Control of Reconfigurable Multi-Agent Systems in Uncertain Adversarial Environments

5a. CONTRACT NUMBER
   61102F

5b. GRANT NUMBER
   FA9550-12-1-0366

5c. PROGRAM ELEMENT NUMBER
   61102F

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
   ARIZONA UNIV BOARD OF REGENTS TUCSON
   888 N. EUCLID AVENUE
   TUCSON, AZ 85722-3308 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
   AF Office of Scientific Research
   875 N. Randolph St. Room 3112
   Arlington, VA 22203

10. SPONSOR/MONITOR’S ACRONYM(S)
    AFRL/AFOSR RTA2

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
    A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
   In this last period, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems. Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we proposed a hybrid observer that not only guarantees very fast performance but also total rejection of perturbations. The class of noise signals our observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to networked systems. We also generated estimation and synchronization algorithms for two agents that operate under intermittent information. We were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival of new information. The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drops.

15. SUBJECT TERMS
    Reconfigurable Multi-agent Systems, Decentralized Control

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<table>
<thead>
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<th>16. SECURITY CLASSIFICATION OF:</th>
<th>17. LIMITATION OF ABSTRACT</th>
<th>18. NUMBER OF PAGES</th>
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<td>a. REPORT Unclassified</td>
<td>b. ABSTRACT Unclassified</td>
<td>c. THIS PAGE</td>
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19a. NAME OF RESPONSIBLE PERSON

Jeffrey Jacobs

19b. TELEPHONE NUMBER

(Include area code)

520-621-8459

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https://livelink.ebs.afrl.af.mil/livelink/lisapi.dll

10/23/2015
Grant/Contract Title: (YIP) ROBUST FEEDBACK CONTROL OF RECONFIGURABLE MULTI-AGENT SYSTEMS IN UNCERTAIN ADVERSARIAL ENVIRONMENTS

Grant/Contract Number: FA9550-12-1-0366

Start period 07/01/2012
End 06/30/2015

Accomplishments:

During the first review period, one of our most exciting contributions has been on the topic of distributed estimation with performance and robustness guarantees. The tradeoff between performance, namely, rate of converge of the estimates, and robustness to external disturbances (being measurement noise the most challenging disturbance to cope with) is a long standing limitation of state observers. Current linear observer structures that guarantee a fast rate of convergence of the estimates unavoidable amplify measurement noise. To overcome this limitation, we have proposed a new observer structure and design methodology, which we call “coupled multi-observers”, that, when compared to current linear observers, yield observers with improved rate of convergence and robustness to measurement noise. The new structure consists of multiple observers coupled in a clever way so that they observe the same process from different “viewpoints” and extract as much information as possible from the measurements. The design procedure is constructive and presented as computationally tractable optimization problems. Our new observer is an exciting breakthrough for the increasing need to estimate variables with good performance and robustness guarantees, especially when applied to distributed settings where uncertainty in the measurements is prominent. The other important contributions in this review period pertain to the use of hybrid methods in distributed settings and the design of numerical methods to properly compute their trajectories. We have generate results showing that hybrid observers can guarantee finite time convergence of the estimate with robustness, that synchronization (and desynchronization) of time in a network is a property that is robust to time skews and packet losses, and, for more general hybrid systems, we have developed constructive state-feedback laws for stabilization of compact sets.

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During the second review period, our most exciting contributions have been on distributed robust estimation with performance guarantees and hybrid methods for the analysis and design of multi-agent systems. The tradeoff between performance, namely, rate of converge of the estimates, and robustness to external disturbances (being measurement noise the most challenging disturbance to cope with) is a long standing limitation in the design observers for single plants, which, unavoidable, is also a key limitation in estimation for multi-agent systems. To overcome this limitation, we have proposed a novel distributed observer structure and design methodology, which we call “interconnected observers”, that, when compared to current distributed observers, yield local and global observers with improved rate of convergence and robustness to measurement noise as well as optimized communication graph. The new structure consists of distributed observers sharing information between nodes at the dynamic level, which is what differentiates our approach from other works where the information is shared at the output level through the computation of averages of the estimates. In fact, we were able to show that the average of the estimates does not alleviate at all the effect of worst case measurement noise. The design procedure of our interconnected observers is constructive and presented as computationally tractable multi-objective optimization problems.

During this period, our work on this topic was recognized by AACC as a finalist for the Best Student Paper Computation at the 2014 American and Control Conference in Portland. The other important contributions in this review period pertain to the use of hybrid methods for robust global stabilization of underactuated nonlinear systems and for the study of distributed hybrid systems. We have generate results establishing that hybrid backstepping techniques can be applied to design controllers for vector-thruést vehicles that are robust to unmodeled dynamics, which is a key step toward the design of control algorithms for multiple vehicles. Hybrid methods were also applied to the analysis of distributed hybrid systems in the context of complex networks of spiking neurons for the study of synchronization and parameter sensitivity.
Also during the second period, our work on this topic was recognized by the *SIAM Control and Systems Theory Prize for contributions to analysis and syntheses of hybrid feedback control systems.*

During the third and last review period of this project, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems. Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we proposed a hybrid observer that not only guarantees very fast performance but also total rejection of a class of perturbations. More precisely, for linear time-invariant systems with noisy output measurements given by a function of the state, we designed an observer with state-triggered jumps that provides an estimate that converges to the true value of the state after tunable finite amount of time. The class of noise signals our observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to networked systems. The interest in finite time convergence has led us to the development of analysis and design tools for finite time stability for hybrid systems (single and multi-agents) with robustness, which is typically a missing link (for continuous-time, discrete-time, and hybrid systems). During this period, we also generated estimation and synchronization algorithms for two agents that operate under intermittent information. More precisely, we were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival of new information. The times that the transmission/reception of information occur has to satisfy some mild conditions that depend on the dynamics of each of the systems (especially if those are unstable). The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drop outs. More importantly, the modular nature of the algorithms suggests that they can be further developed to work in agents that are networked, heterogeneous and under the effect of perturbations. Such is the theme of our current proposal under review on estimation and synchronization in complex networks.
Archival publications:

Submitted: (7 journal and 9 conference submissions)


Sanfelice, R. G. & Praly, L., Convergence of Nonlinear Observers on $\mathbb{R}^n$ with a Riemannian Metric (Part II), Submitted to IEEE TAC, 2015.

Li, Y. & Sanfelice, R. G., A Decentralized Consensus Algorithm for Distributed State Observers with Performance and Robustness Guarantees, Submitted to CDC, 2015.


Sanfelice, R. G. & Praly, L., Solution of a Riccati Equation for the Design of an Observer Contracting a Riemannian Distance, Submitted to CDC, 2015.


Published: (3 book chapters, 17 journal articles, and 40 conference articles)


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1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.
ricardo@ucsc.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report.
831-459-1016

Organization / Institution name
University of California

Grant/Contract Title
The full title of the funded effort.
(YIP) ROBUST FEEDBACK CONTROL OF RECONFIGURABLE MULTI-AGENT SYSTEMS IN UNCERTAIN ADVERSARIAL ENVIRONMENTS

Grant/Contract Number
AFOSR assigned control number. It must begin with “FA9550” or “F49620” or “FA2386”.
FA9550-12-1-0366

Principal Investigator Name
The full name of the principal investigator on the grant or contract.
Ricardo G. Sanfelice

Program Manager
The AFOSR Program Manager currently assigned to the award
Fariba Fahroo

Reporting Period Start Date
07/01/2012

Reporting Period End Date
06/30/2015

Abstract
In this last period, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems. Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we proposed a hybrid observer that not only guarantees very fast performance but also total rejection of perturbations. The class of noise signals our observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to networked systems. We also generated estimation and synchronization algorithms for two agents that operate under intermittent information. We were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival of new information. The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drops.

Distribution Statement
This is block 12 on the SF298 form.

DISTRIBUTION A: Distribution approved for public release.
Archival Publications (published) during reporting period:


Zhang, K., Sprinkle, J. & Sanfelice, R. G., A Hybrid Model Predictive Controller for Path Planning and Path


Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

N/A

Extensions granted or milestones slipped, if any:

N/A

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)
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Appendix Documents

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