INFORMATION FLOW IN COOPERATIVE CONTROL OF MULTI-VEHICLE SYSTEMS

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Richard Murray Alex Fax[1]
Control and Dynamical Systems
California Institute of Technology
Pasadena, CA 91125

1 Objectives

This project is focused on developing the underlying theory required to achieve integration of information flow into control analysis and design for cooperative tasks of multi-vehicle systems. By making use of tools from control theory, dynamical systems, and graph theory, we are developing a framework for analyzing the effects of information and sensor topology on feedback systems and developing tools for designing information flow and control algorithms that build on this framework. We are applying these ideas to several test problems involving real-time, distributed control of a set of multiple vehicles performing cooperative tasks. In addition to computational exploration through simulation, we plan to implement our algorithms on a multi-vehicle, wireless testbed for networked control, communications, and computing that is being developed at Caltech.

2 Status of Effort

We have obtained an initial set of results that related the topology of the underlying communications network to the stability of the overall system, under the assumption of identical linear dynamics for each vehicle (nodes). The conditions for stability are given as a simple Nyquist test, with the -1 point replaced by the inverse eigenvalues of the Laplacian associated with the graph. We are also able to design the information flow of the system so that the vehicles achieve consensus about shared information, such as the location of the center of the formation. We are extending this work in a number of directions, including application to nonlinear systems, investigation disturbance rejection properties, and use of more accurate descriptions of the communications channels.

[1]Now at Northrop Grumman

3 Accomplishments

Graph Laplacians and Formation Stability

Control of vehicle formations has emerged as a topic of significant interest to the controls community. We have used tools from graph theory and control theory to derive a simple stability criteria for formation stabilization. The interconnection between vehicles (i.e., which vehicles are sensed by other vehicles) is modeled as a graph, and the eigenvalues of the Laplacian matrix of the graph are used in stating a Nyquist-like stability criterion for vehicle formations. The location of the Laplacian eigenvalues can be correlated to the graph structure, and therefore used to identify desirable and undesirable formation interconnection topologies.

Building on this work, we have considered the problem of information flow in multi-vehicle systems. Vehicles in formation often lack global information regarding the state of all the vehicles, a deficiency which can lead to instability and poor performance. We have demonstrated how exchange of minimal amounts of information between vehicles can be designed to realize a dynamical system which supplies each vehicle with a shared reference trajectory. When the information flow law is placed in the control loop, a separation principle is proven which guarantees stability of the formation and convergence of the information flow law regardless of the information flow topology.

Together, these results provide a framework for analyzing the stability of interconnected systems and understanding the relationship between the individual vehicle dynamics and the topology of the communications network through which the vehicles share information. Current work is aimed at extending these results to nonlinear systems and analyzing disturbance rejection properties (so-called string stability) using graph Laplacians.

Uncertain Communications Channels

Our work on graph Laplacians considers only the topology of the network connecting vehicles. In more realistic situations, one would like to have a more accurate model of the communications channel and understand the effects of the channel dynamics on the system performance. We have begun exploration of this path by studying techniques for jump Markov processes, in which each Markov state corresponds to a given channel configuration. This framework can be used to model channels with varying delay, bandwidth, or SNR properties through a discrete collection of models.

Prior work in this area had shown that if the Markov state was known, it was possible to stabilize the jump Markov system under certain conditions. These conditions related to individual Markov state dynamics to the transition rates between the Markov states. In preliminary work, we have extended these results to allow the Markov state to be estimated (using, for example, the Viterbi algorithm). These results allow us to design control laws for the different communication channel conditions and interconnect them to achieve stability in the presence of uncertain channel conditions.

Multi-Vehicle Wireless Testbed

The techniques developed under this grant are being implemented on the Caltech multi-vehicle testbed. The testbed consists of 8 mobile vehicles with embedded computing and communications capability. A unique feature of the testbed is the use of vehicles that have second order dynamics, requiring real-time feedback algorithms to stabilize the system while performing cooperative tasks.

Students supported by this project have been involved in implementing control laws for the testbed as well as developing the Bluetooth communications capability. This infrastructure will be used in the next year to test new results for control of interconnected systems.

4 Personnel Supported

Faculty
Richard Murray, Caltech

Graduate students
Alex Fax, Caltech
Lars Cremean, Caltech
Abhishek Tiwari, Caltech
Vijay Gupta, Caltech

5 Publications

- L. Cremean, W. Dunbar, D. van Gogh, J. Hickey, E. Klavins, J. Meltzer, R. M. Murray, The Caltech Multi-Vehicle Wireless Testbed. To appear, 2002 Conference on Decision and Control (CDC)
- J. A. Fax and R. M. Murray, Information Flow and Cooperative Control of Vehicle Formations. IFAC World Congress, 2002.
- J. A. Fax and R. M. Murray, Graph Laplacians and Stabilization of Vehicle Formations. IFAC World Congress, 2002.
- J. A. Fax, Optimal and Cooperative Control of Vehicle Formations. PhD Dissertation, Control and Dynamical Systems, California Institute of Technology, 2001.

6 Interactions and Transitions

Meetings and conferences

Richard Murray visited Eglin AFB and gave a presentation at the University of Florida Graduate Education and Research Center (GERC) on 27-28 June 2002.

Alex Fax presented results of this work were presented at the International Federation of Automatic Control (IFAC) World Congress on 22-26 July 2002 in Barcelona.

Consulting and advisory functions

Richard Murray has participated in several advisory functions to the Department of Defense:

- Member of the Information Science and Technology (ISAT) Study Group, making recommendations to DARPA about long term research directions, 2000–present.
- Participated in SBIRS High Technology Review for the Director of Defense Research Engineering, Dr. Ronald Sega, April 2002.
- *Ad hoc* member of the Air Force Scientific Advisory Board review team for the Air Vehicles Directorate, December 2001.
- Served as chair for the Panel on Future Directions in Control, Dynamics, and Systems. Report release April 2002.

Transitions

None to date.

New Discoveries, Inventions, or Patent Disclosures

None to date.