COOPERATIVE CONTROL OF DISTRIBUTED AUTONOMOUS VEHICLES IN ADVERSARIAL ENVIRONMENTS

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Abstract

The goal of this MURI project is to develop the tools required for the systematic design of cooperative control systems for distributed vehicles in adversarial environments. The project is a collaborative effort between the participating institutions of Caltech, Cornell, MIT, and UCLA. The following "dimensions" of cooperative control offer an effective breakdown of the cooperative control landsacpe: 1) Distributed control and computation, 2) Adversarial interactions, 3) Uncertain evolution, and 4) Complexity management. The five year MURI effort has identified and addressed many subproblems in the cooperative control landscape and has produces both simulation and hardware testbeds.

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14. ABSTRACT
The goal of this MURI project is to develop the tools required for the systematic design of cooperative control systems for distributed vehicles in adversarial environments. The project is a collaborative effort between the participating institutions of Caltech, Cornell, MIT, and UCLA. The following ``dimensions'' of cooperative control offer an effective breakdown of the cooperative control landsacpe: 1) Distributed control and computation, 2) Adversarial interactions, 3) Uncertain evolution, and 4) Complexity management. The five year MURI effort has identified and addressed many subproblems in the cooperative control landscape and has produces both simulation and hardware testbeds.

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Selected Research Highlights

Over the past 5 year, the MURI has involved 26 students, 8 postdocs, and 13 university faculty members, resulting in over 100 publications.

The following are selected highlights of research conducted under this MURI:

Consensus in Switching Topology Networks & Reynolds's Flocking Rules: Vehicle flocking can be viewed in the context of a network of communicating agents in which communication links persistently change. A basic paradigm for decision making over networks is the notion of "consensus", in which the collective of agents reaches a mutual agreement despite the switching network topology. This work introduced the notion of a "balanced" graph and established that consensus is achievable under this property. This work also led to the first complete analytical justification of the widely popular "Flocking Rules of Reynolds" (separation, alignment, & cohesion), introduced in 1987 as a heuristic for inducing flocking behavior among virtual vehicles.

Representative publications:

- R. Olfati-Saber and R.M. Murray, "Consensus problems in networks of agents with switching topology and time-delays", *IEEE Transaction on Automatic Control*, September 2004.
- R. Olfati-Saber, "Flocking for multi-agent dynamic systems: Algorithms and theory", *IEEE Transactions on Automatic Control*, March 2006.

Computation and control language programming environment: Design of distributed systems, indeed any design process, will involve design iterations and exploratory simulations. This work facilitates such a process tailored to distributed systems through a programming environment based on the Computation and Control Language (CCL). CCL is a guarded-command language for expressing systems wherein control and computation are intertwined. The environment exploits automated verification methods to aid in the development of distributed decision making protocols with guaranteed performance properties.

Representative publications:

- E. Klavins, “A language for modeling and programming cooperative control systems”, *Proceedings of the International Conference on Robotics and Automation*, 2004.
- E. Klavins and R.M. Murray, “Distributed algorithms for cooperative control”, *IEEE Pervasive Computing*, January 2004.
- E. Klavins, “A formal model of a multi-robot control and communication task”, *Proceedings of the 42nd IEEE Conference on Decision and Control*, December 2003.

Mixed-integer LP methods for multivehicle systems: This work considers trajectory planning for multiple vehicles in the presence of an invading team. The objective is to disable invaders before they reach a critical defense zone. This work introduces an abstraction of this problem called the “RoboFlag Drill”. The RoboFlag drill serves as a motivating and illustrating challenge problem for several components of the MURI activities. Because of the binary nature of an invader being active or disabled, the resulting optimization has a combinatorial aspect. This work shows how mixed-integer linear programming tools, which are commercially available, can be used to derive nominal intercepting trajectories. Complementary work shows how simplifying assumptions can lead to reduced complexity computations, using only LP’s.

Representative publications:

- M. G. Earl and R. D’Andrea, “A Study in Cooperative Control: The RoboFlag Drill”, *Proceedings of the American Control Conference*, 2002.
- M. Earl and R. DAndrea, “Iterative MILP methods for vehicle control problems”, *IEEE Transactions on Robotics*, 2005.
- G. Chasparis and J. Shamma, “Linear-Programming-Based Multi-Vehicle Path Planning with Adversaries”, *Proceedings of the American Control Conference*, June 2005.

Finite state mode estimation: Because of either limited communications or restricted information, there is uncertainty between vehicles in knowledge of each other’s state. Here, the intent is not traditional notions of state estimation, but rather “state” is being used as “mode of operation”. Understanding the mode of operation is important for determining consensus among teammates or assessing the intent from adversaries. This work takes two complementary approaches to mode estimation. The first approach uses completely finite state models. While one may construct a sort of set-valued observer, such an approach would be computationally prohibitive. Rather, this work constructs an observer that takes advantage of the special structures that allow simplified observer representations. The second approach is a hybrid setting of continuous dynamics with probabilistic mode changes. This work develops a mode observer that capture the tradeoff between rates of mode transitions and accuracy of mode estimations.

Representative publications:

- D. Del Vecchio, R. M. Murray and E. Klavins, "Discrete state estimators for systems on a lattice", *Automatica*, 2006.
- N.C. Martins and M. A. Dahleh, "An Information Theoretic Approach to the Mode Estimation of Randomly Switching FIR Systems", *Proceedings of the IEEE Mediterranean Control Conference*, 2003.
- D. Choukroun, Speyer, J.L., "Mode-Estimator-Free Quadratic Control of Jump-Linear Systems with Mode-Detection Random Delay", *Proceedings of the AIAA Guidance, Navigation, and Control*, 2005.

Distributed convergence to Nash equilibria: Noncooperative game theory has long been a paradigm for investigating strategic mechanisms with hostile adversaries. In min-max or zero-sum games, there is a tacit assumption that each adversary knows the intention of the other. An important question is what happens when intentions are *not* shared. One can still define concepts such as a Nash equilibrium in this case, but an unresolved question in game theory is how a Nash equilibrium could emerge through interactions of bounded rationality players. This work has shown that Nash equilibria can emerge by viewing adversarial interactions as a feedback system. The resulting analysis and simulations produce convergent behaviors in long standing (40 years) counterexamples suggesting that Nash equilibria will not emerge.

Representative publications:

- J.S. Shamma and G. Arslan, "Unified convergence proofs of continuous time fictitious play", *IEEE Transactions on Automatic Control*, July 2004.
- J.S. Shamma and G. Arslan, "Dynamic fictitious play, dynamic gradient play, and

distributed convergence to Nash equilibria", *IEEE Transactions on Automatic Control*, March 2005.

Differential games with probabilistic models: Many representations of adversarial behavior presume a "worst case" situation. This framework alone does not capture many attrition models that use probabilistic models to represent adversarial encounters. A more appropriate optimization in this case is a combination of worst case modeling and expected value analysis. This work considers such a framework for linear-quadratic games, in which strategies are derived that optimize against both worst case opponent and a neutral, but probabilistic, environment. The work shows that—contrary to conjectures in earlier literature that suggested infinite dimensional optimal controllers—the ensuing optimal controllers may well have a familiar model based structure.

Representative publications:

- A. Swarup and J.L. Speyer, "Characterization of Linear Quadratic-Gaussian Differential Games with Different Information Patterns", *IEEE Conference on Decision and Control*, 2004.
- A. Swarup and J.L. Speyer, "Handling Partial and Corrupted Information," in *Advanced Technology Concepts for Command and Control: An Anthology of Feedback-Based Approach to Command and Control*, A. Kott (editor),CRC/Taylor and Francis, 2005.

Optimal navigation in partially unknown environments: In distributed vehicle systems, each vehicle has local information which can be shared with team members. There is an inherent trade-off in such operations, namely the tension between dispersion for the sake of information gathering and cohesion for the sake of information exploitation. In other words, if vehicles form a sparse spread, then they may gather more information but are not sufficiently close to benefit from shared information. This work addresses this trade-off in a quantifiable manner through the investigation of navigation in partially unknown environments. The work uses a dynamic programming framework to determine optimal distancing that balances the dispersion/cohesion trade-off.

Representative publications:

- J. De Mot and E. Feron, "Spatial Distribution of Two-Agent Clusters for Efficient Navigation", *Proceedings of the IEEE Conference on Decision and Control*, 2003.
- J. De Mot and E. Feron, "Optimal Two-Agent Navigation with Local Environment Information", *Allerton Conference on Control and Communications*, 2004.

Control under communication constraints: Coordinated interaction of multiple vehicles will inevitably require networked communications. This work investigates control performance limitations imposed by controller implementations over a network. In particular, this work explores the trade-off between communications channel capacity and robust stabilization through analytical bounds that are not restricted to any specific form of a controller or coding scheme, and, as such, provide ultimate limits of achievable performance.

Representative publications:

- N.C. Martins, M.A. Dahleh, and N. Elia, "Stabilization of Uncertain Systems in the Presence of a Stochastic Digital Link", *Proceedings of the IEEE Conference on Decision and Control*, 2004. (Extended version submitted to the IEEE Transactions in Automatic Control).
- N.C. Martins and M.A. Dahleh, "Fundamental Limitations of Disturbance Attenuation in the Presence of Finite Capacity Feedback", *Proceedings of the American Control Conference*, 2005. (Extended version submitted to the IEEE Transactions in Automatic Control).
- S. Sarma and M.A. Dahleh, "Remote Control over Noisy Communication Channels: A first order example", Accepted for publication, *IEEE Transactions on Automatic Control*, 2006.

Language Evolution: This work is indirectly related to the problem of consensus. The question is to understand the limiting behavior of interacting populations that use different grammars/languages, e.g., whether there will be a single dominant language or a distribution of languages. A relation to multivehicle systems is understanding how highly autonomous vehicles on extended missions will be able to communicate the presence of entities that were not previously encountered.

Representative publications:

- Y. Lee, T.. C. Collier, G. M. Kobele, E. P. Stabler and C. E. Taylor. "Grammar structure in language evolution", *European Conference on Artificial Life*, 2005.
- Y. Lee, T. C. Collier, E. S. Stabler and C. E. Taylor. "The role of population structure in language evolution". in M. Sugisaka and H. Tanaka, eds., *Proceedings of the Tenth International Symposium on Artificial Life and Robotics*, 2005.

Probability maps of environments with moving opponents: Trajectory planning in uncertain environments requires the existence of some sort of map of threat probabilities. In the case of a non-stationary environment, such a probability map must be updated to reflect threat evolution due to moving adversaries. This work develops tools for the construction and evolution of such probability maps. The work goes on to investigate the role of such maps in multivehicle path planning. Again, a trade-off emerges between the potential benefits and associated risks of exploration. The presence of moving opponents further complicates such issues.

Representative publications:

- M. Jun and R. D'Andrea, "Probability map building of uncertain dynamic environments with indistinguishable obstacles", *Proceedings of the American Control Conference*, 2003.
- V.G. Rao and R. D'Andrea, "Managing Multiple Moving Vehicles with Patch Representations", *Fifth Annual Conference on Cooperative Control and Optimization* (CCO '05), 2005.

Personnel Supported During Duration of Grant

These include:

Faculty	*Postdocs*
Jason Hickey, Caltech (CS)	Eric Klavins, Caltech
Richard Murray, Caltech (ME/CDS)	Reza Olfati-Saber, Caltech & UCLA
Raffaello D'Andrea, Cornell (MAE)	Myungsoo Jun, Cornell
Carla Gomes, Cornell (CS)	Venkatesh G. Rao, Cornell
Munther Dahleh, MIT (EECS)	Vishwesh Kukharni, MIT
Eric Feron, MIT (AA)	Nuno Martins, MIT
Steve Massaquoi, MIT (EECS/HST)	Gurdal Arslan, UCLA
Jeff Shamma, UCLA (MAE)	Jonathan Wolfe, UCLA
Jason Speyer, UCLA (MAE)	
Edward Stabler, UCLA (Lin)	
Charles Taylor, UCLA (Bio)	
Past participants	
Brian Williams, MIT (AA)	
Greg Pottie, UCLA (EE)	

Students

Zhipu Jin, Caltech	Holly Waisane, MIT
Steve Waydo, Caltech	Ibrahim Al-Shyoukh, UCLA
Atif Chaudhry, Cornell	George Chasparis, UCLA
Matthew Earl, Cornell	Travis Collier, UCLA
Jeff Fowler, Cornell	Gregory Kobele, UCLA
Cedric Langbort, Cornell	Amish Pandya, UCLA
Jan De Mot, MIT	Yoosook Lee, UCLA
Sommer Gentry, MIT	Ying Lin, UCLA
Georgious Kotsalis, MIT	Jason Marden, UCLA
Nuno Martins, MIT	Jason Riggle, UCLA
Zhi-Hong Mao, MIT	Vincent Seah, UCLA
Eugene Lim, MIT	Ashitosh Swarup, UCLA
Sridevi Sarma, MIT	Yuan Yao, UCLA

AA: Aeronautics & Astronautics, Bio: Ecology and Evolutionary Biology, CDS: Control and Dynamical Systems, CS: Computer Science, EECS: Electrical Engineering and Computer Science, HST: Health Sciences and Technology, Lin: Linguistics, MAE: Mechanical and Aerospace Engineering, ME: Mechanical Engineering.

Several of the MURI alumni have gone on to faculty positions of their own. These include:

- Gurdal Arslan: University of Hawaii
- Daniel Choukroun: Ben Gurion University
- Domitilla Del Vecchio: University of Michigan
- Eric Klavins: University of Washington
- Nuno Martins: University of Maryland
- Zhi-Hong Mao: University of Pittsburgh
- Reza Olfati-Saber: Dartmouth College

Publications

The MURI has resulted in over 100 publications. A comprehensive list and many electronic copies are available at: `http://www.seas.ucla.edu/coopcontrol/`.

In addition to these publications, there will be an edited collection stemming from the work of this MURI entitled *Cooperative Control of Distributed Multi-Agent Systems* to be published by John Wiley & Sons.

Honors & Awards Received

- Arslan: NSF CAREER Award
- Dahleh: IEEE Fellow, IEEE Axelby Award, Plenary Speaker: MTNS, SyDyC Student Symposium (UCLA)
- DAndrea: RoboCup 2nd, 1st, 2nd, 3rd, 1st (2000-2005), NSF CAREER & PECASE Award, Plenary Speaker: Cellular Automata Conf, Robot Motion Control Conf, SIAM Conf on Control and its Applications; Distinguished Lecturer Rome Labs, NASA Langley, MTNS.
- Klavins: NSF CAREER Award
- Martins & Dahleh: Hugo Schuck Award

- Murray: IEEE Fellow, Plenary Speaker: 2003 ECC, 2005 ACC, 2006 ASCC, SyDyC Sutdent Symposium (UCLA)
- Shamma: IEEE Fellow
- Speyer: NAE Member, AIAA Fellow, IEEE Fellow

Interactions and Transitions

- Arslan: Lockheed Martin Orincon, "Autonomous Sensor Allocation for Submarine Tracking".
- Dahleh & Shamma: AFOSR Award ($600K), "Control Theoretic Modeling for Uncertain Cultural Attitudes and Unknown Adversarial Intent".
- Feron: Nascent Tech Corp Navy STTR & DARPA SBIR; Advisory Board of French National Academy of Technologies.
- Murray & Klavins: AFOSR MURI, "High Confidence Design for Distributed Embedded Systems".
- Murray: Member, National Research Council (NRC) Panel on Network Science, 2005; Member, Air Force Scientific Advisory Board, 2002-present; Chair, Panel on Future Directions in Control, Dynamics and Systems, 2000-2002; Chair, Collaborative Center on Control Science (CCCS) Executive Board, 2002-present.
- Shamma: REEF Research Advisory Board; Speaker, NRC Workshop on NASA Relationships for Technology Development.
- Speyer: Member, NRC Panel on Decadal Survey of Civil Aeronautics; SySense, Inc. Phase II SBIR with BMD.
- Taylor: NSF Award ($1M), "Sensor Arrays for Monitoring Bird Behavior and Diversity".