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14. ABSTRACT A fundamental challenge in designing networked control systems is that communication and control are not, in general, decoupled from each other. In order to address this challenge, the methods used in this project fundamentally integrated the tools, capabilities and constraints of both control theory and networking. The proposed solution enabled leveraging of existing seminal works in both fields. It also allowed for a cross-layer rethinking of the wireless networks for control applications. In particular, results both in theory and experiment showed that the above analysis can be extended and used to balance the performance of the controller and energy efficiency of communication schemes. Via an integrated set of simulations, the proposed design was illustrated not only in terms of the dynamical performance of formations, e.g. rate of convergence, but also in terms of energy efficiency and communication overhead. Vehicles were modeled as constant speed with controlled heading and were given the task of inducing the group centroid to track a target. Dynamic communication was incorporated via discretization of the dynamics, and nonlinear coordinated control was based on oscillator models. Results were demonstrated in simulation and in hardware.					
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Hierarchical Integrated Communication and Control

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ABSTRACT

A fundamental challenge in designing networked control systems is that the tasks of communication and control are not, in general, decoupled from each other. In order to address this challenge, the methods used in this project fundamentally integrated the tools, capabilities and constraints of both control theory and networking. The proposed modularized solution enabled leveraging of existing seminal works in both fields. It also allowed for a cross-layer rethinking of the wireless networks for control applications. In particular, our results, both in theory and experiment, showed that the above analysis can be extended and used to balance the performance of the controller and energy efficiency of communication schemes.

Via an integrated set of simulations, the proposed design was illustrated not only in terms of the dynamical performance of formations, e.g. rate of convergence, but also in terms of energy efficiency and communication overhead. Vehicles were modeled as constant speed with controlled heading (suitable for many air, land, water surface, and underwater applications) and were given the task of inducing the group centroid to track a target. Dynamic communication was incorporated via discretization of the dynamics, and nonlinear coordinated control was facilitated using Kuramoto oscillator models.

1. OBJECTIVES AND SIGNIFICANCE

The objective of our work was to design integrated control and communication algorithms that guarantee that a set of vehicles with nonlinear dynamics connected via a wireless communication network would achieve particular coordination tasks such as maintaining sensor coverage of an object of interest. Unlike most coordinated control settings, we were not only interested in the question of coordinated control, but also the question of reliably providing the communication necessary to achieve the coordination. The three primary tasks that were addressed as part of the work were:

1. construct hierarchical coordinated control algorithms,
2. identify minimal energy communication topologies to enable the control tasks, and
3. demonstrate the performance of the system in simulation and on a physical test-bed.

The topic of coordinated control and communication has been receiving growing interest in the last several years due to the broad range of applications for which the topic has been able to produce relevant results. The approaches that have been taken to coordinated and/or cooperative control of multi-vehicle systems utilize a range of sensed and/or communicated data. Early work in the area of coordinated robots relied primarily on the use of sensor information. Methods of data transmission based only on sensing have been studied in a number of scenarios. However, none of these scenarios allowed dynamic group behavior at the level of complexity possible if at least some communication is allowed. The use of transmitted information, while more complicated, provides data that is not as easily disrupted by the presence of obstacles in the environment.

Prior techniques for the use of coordinated control with communication generally assumed continuous and uninterrupted transmission. Studies of static communication patterns among

vehicles had shown that certain patterns prevent convergence to desired group behaviors. When dynamic communication patterns were allowed, different choices of patterns could be shown to either stabilize or destabilize group behaviors. Successful use of these results depended on being able to maintain particular communication patterns which may not be possible in a dynamic operating environment. For dynamic communication, issues of consensus and transmission sequences must be considered. Each of these approaches, static and dynamic, assumed that all vehicles will be communicating. These studies produce a homogeneous setting that does not explicitly allow for vehicles with differing data collection capabilities—specifically data collected only from sensing in comparison to data collected from both sensing and communication. A unique feature of the work from this AFOSR project was our focus on developing decentralized algorithms for both establishing an efficient communication network and also for the coordinated control under practical and realistic settings.

The methods developed here have wide applicability to Air Force needs in autonomous systems. In particular, the consideration of network performance for low data rates is of great interest for both autonomous and manned systems in adversarial situations where large bandwidth could be intercepted. Beyond the immediate applications to control of multiple autonomous vehicles, these results provide tools for use in MEMS systems, control of internet traffic, and insight into mechanisms for self-organizing biological systems.

2. SIGNIFICANT ADVANCEMENTS

The overall conceptual framework behind the work in this project is illustrated in Figure 1. The components of the algorithm and process, as well as the results, are detailed below.

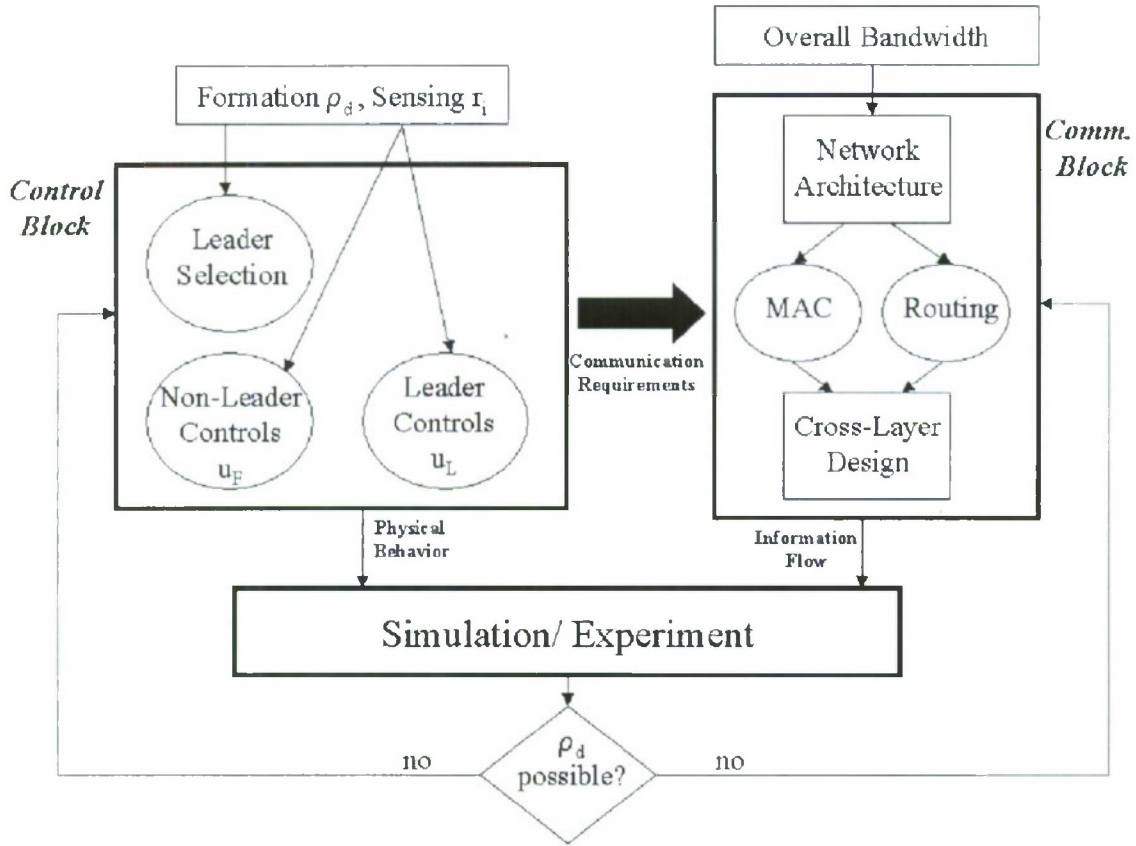


Figure 1: Iterative design process for integrated communication and control.

2.1. Oscillator models for nonlinear coordinated control

Given a set of N vehicles with nonlinear dynamics as discussed above, heading control was created from a superposition of alignment and spacing terms where the time scales of the two are assumed to be such that they decouple. The form of the alignment control was then chosen to be that of a system of coupled phase oscillators. This choice produced a system where stability analysis was analytically tractable. In [2,4], we showed how to incorporate a reference velocity term, feedforward information of target motion, and outer loop control to produce tracking of a dynamically moving target using three vehicles either in the plane or in 3D.

In order to incorporate dynamic communication, we addressed the stability of discretized oscillator models in the presence of delay and dynamic communication. The case of discretized oscillator models with all-to-all communication and constant fixed delay was considered in [1] where we showed that stability of the system was determined by a bound on $K\Delta$ where K is the coupling gain and Δ is the discretization interval. Extending these results to a one-to-all broadcast setting, we showed that selecting the transmitting vehicle randomly allowed us to determine stability bounds on feedback gains that will produce either synchronized (identical) headings (see Figure 2) or headings that average to zero [3].

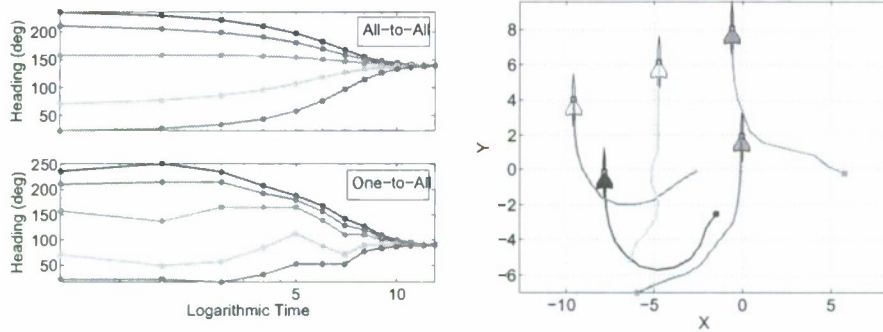


Figure 2: Coordinated heading control with the discrete time Kuramoto model is shown for a group of five vehicles. (a) The vehicle headings using all-to-all (top) and one-to-all random broadcast (bottom) communication topologies for $K = -0.5$ and $\Delta T = 1$. (b) Vehicle trajectories corresponding to the one-to-all random broadcast heading control.

In this setting, the scenarios of one-to-one and one-to-all broadcasting were considered. The communication network protocols and setup were assumed to guarantee that all vehicles can receive data from at least one other vehicle and that no physical obstructions to the signal path were present. In reality, transmission times will differ between vehicles, some transmissions may fail, and timing may be asynchronous, even though the network was designed such that state information can be shared on any logical link in one discretization interval. The effect of these constraints is that the communication network for the multi-vehicle system is time-varying.

2.2. QoS communication over logical graphs

Based on the above results, we developed an initial coupling between communication and control based on the discretization interval. These results produce bounds on system performance for a simple task and an optimal choice of network topology. In the coordinated control model above, an edge represents availability of information at discrete times from one node to its logical neighbor. In reality, such information from one vehicle to the next needs to be transferred as bits using an underlying communications network. The second element of our work, hence, consisted of the realization of a logical graph via real-time and energy efficient delivery of digitized information. In other words, communication protocols and algorithms have been established for efficient and delay-sensitive delivery of information packets over the given graph, resulting in the practical use of the wireless bandwidth by communication nodes.

Clearly, in a wireless setting, all logical broadcast trees are feasible given sufficient transmission power. In other words, the realization of a particular logical broadcast tree depends on the transmission power at each vehicle, which determines the network graph supporting the broadcast logical graph. Notice that edges in a networking graph correspond to one-hop transmissions while the edges in logical graphs represent dissemination of state information over the edge in Δ seconds, which may correspond to one or more hops. The simplest broadcast realization is materialized when the transmission power at the root of the tree (transmitter) is chosen sufficiently large in order to guarantee that the farthest node can be reached in one hop, creating a star network graph, while more complicated realizations would schedule transition at various nodes. In this work, we were interested in finding realization which minimizes the total energy consumed for communication.

From this wireless networking perspective, we obtained results on an energy optimal realization of each broadcast tree which transfers B bits of information (representing state information) from a single vehicle to all others in Δ seconds. In [3], we investigated and identified topological conditions under which various strategies are optimal. In particular, we have shown that the hard deadline Δ drastically changes the nature of the minimum energy multi-cast (hence broadcast) tree. More specifically, we demonstrated an un-intuitive relationship between B , Δ , and optimal hop length. For instance, we showed that a star topology (single hop network) outperforms any multi-hop scheme when B/Δ is greater than a threshold (see Figure 3). More interestingly, the optimality of the single hop scheme is independent of network topology, and hence the specific aspects of desirable formation. This result is in sharp contrast with construction of minimum energy multi-cast trees for elastic (delay tolerant) traffic.

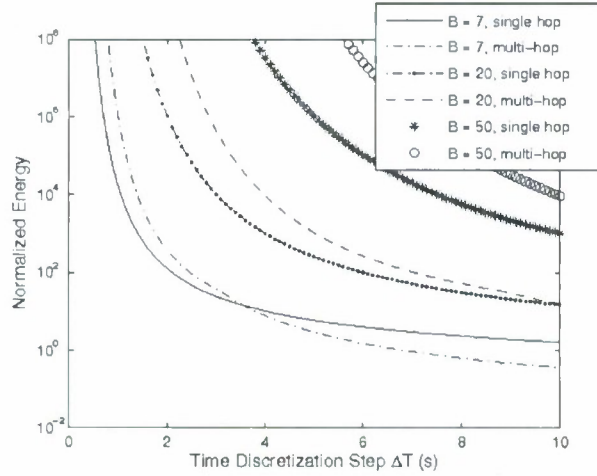


Figure 3: Total communication (normalized by noise) energy versus time discretization step, ΔT , for various levels of quantization, M , for a linear network.

We note that the choice of B depends on the chosen level of quantization of state variables, while the choice of Δ determines the upper bound on delay in dissemination of state information among logical neighbors. On the other hand, the delay and precision with which state variables

are shared in the network have a direct impact on the stability and controllability of the formation.

2.3. Cooperative estimation for coordinated target tracking

In this component of the project, constant-speed and non-holonomic pursuit vehicles communicated with each other through a sequence of broadcast transmissions from one vehicle, selected sequentially at each time step, to all other vehicles. This network topology is consistent with a shared communication medium. To explore the question of what data each vehicle should transmit, three possible communication protocols were considered: transmit nothing, transmit one, two, or three recent measurements, and transmit a state estimate. Communicated data arrives delayed, and sensors fail both stochastically and when the line of sight to the target is occluded by an obstacle. Fusion of local measurements and received communications were achieved by a per-vehicle Unscented Kalman Filter (UKF). A behavior-based controller on each vehicle acted to disperse the vehicles about the target while avoiding collisions with other vehicles and obstacles.

The results presented in this topic differ from these previous works in that allowable communication bandwidth per vehicle was assumed to be sufficiently low that recovering the centralized state estimate is not possible. Another difference was the explicit inclusion of sensor-occluding obstacles. The behavior-based control was, unlike previous work, computed in a distributed manner.

Increases in the amount of information used always improved the accuracy of the estimates for all of the pursuit vehicles. However, when measurements were shared between pursuit agents, the results demonstrated that minimal improvement in the estimates was gained when more than three measurements were shared. This result was due to the delay in the older measurements,

which makes the older data less beneficial to improvements in estimate quality. On the other hand, sharing of estimates resulted in superior results. The estimates were only ever delayed by the minimal communication delay of the system, and contained the broadcasting agent's best knowledge of the target state at all times, which included the combination of all of the broadcasting agent's measurements. Sharing of estimates took about the same amount of data per communication step as did sharing five measurements, so the benefits of estimate fusion need to be weighed against the increase bandwidth requirements.

Increases in sensor reliability were shown to be beneficial to estimator performance. However, for a given sensor reliability rate, improvements in the sensor precision of a single agent in the group can have a significant positive impact on the estimator performance. Increases in communication frequency were also demonstrated to improve estimate results.

When the target tracking system was run in a cluttered environment using the behavioral coordinated pursuit algorithm outlined in the paper, the same effects of communication on target state estimator performance were observed. Which behaviors to emphasize in the coordinated target pursuit was shown to depend on the manner in which the obstacles in the environment were arranged. Whichever pursuit algorithm was used, communication of target state information between pursuit agents significantly improved estimate accuracy.

2.4. Issues of delay in wireless communication

The work in this portion of the project addressed wireless communication channels subject to delay effects. In the first component, the problem of delay optimal rate allocation in a (potentially asymmetric) multi-access channel was considered. The rate feasibility region of such a network has been well-studied and has been shown to be of a polymatroid structure. We

considered this problem with unsaturated sources, i.e. jobs arrive at sources at random times and the source has the possibility of being empty. In such a setting, all stable rate allocation policies result in a throughput matched with the average arrival rate. Hence, we were interested in rate allocation policies that minimize expected delay in the system. In this work, we showed that a policy of threshold type was optimal in minimizing the average queueing delay. We studied the average delay criterion as the limit of an infinite horizon discounted cost function when the discount factor approaches 1.

Another component of the work analyzed the high-SNR asymptotic error performance of outage-limited communications with fading, where the number of bits that arrive at the transmitter during any time slot was random but the delivery of bits at the receiver must adhere to a strict delay limitation. Specifically, bit errors were caused by erroneous decoding at the receiver or violation of the strict delay constraint. Under certain scaling of the statistics of the bit-arrival process with SNR, this work showed that the optimal decay behavior of the asymptotic total probability of bit error depended on how fast the burstiness of the source scaled down with SNR. If the source burstiness scaled down too slowly, the total probability of error was asymptotically dominated by delay-violation events. On the other hand, if the source burstiness scaled down too quickly, the total probability of error was asymptotically dominated by channel-error events. However, at the proper scaling, where the burstiness scales linearly with $1/\sqrt{(\log \text{SNR})}$ and at the optimal coding duration and transmission rate, the occurrences of channel errors and delay-violation errors were asymptotically balanced. In this latter case, the optimal exponent of the total probability of error revealed a tradeoff that addressed the question of how much of the allowable time and rate should be used for gaining reliability over the channel and how much for accommodating the burstiness with delay constraints.

2.5. Design and construction of a radio frequency transceiver

The experimental setting used to demonstrate the results from this project was a set of three underwater vehicles. Communication in such environments is necessarily at a low data rate, but such data rates are also of interest for air and space applications to minimize power consumption and prevent message interception. Devices providing wireless communication in underwater environments are not widely available, particularly for small test tanks such as is available at the UW. Therefore, one part of the work performed in this project was the design and construction of a custom transceiver based on radio modules from Linx Technologies and designed to minimize the attenuating effects of the underwater medium. Specifically, a transmitter and receiver form a half-duplex switchable transceiver circuit, and an amplifier was used to extend the range of the transmitter module. The modules use a carrier frequency of 315 MHz and on-off keying (OOK). All communications between robots and the transceiver board are asynchronous at 2400 baud through a transistor-transistor logic (TTL) serial link. Currently, the robots are communicating with full-wave and half-wave wire antennas mounted externally to eliminate any radio loss incurred as a result of an air-water interface. The communication protocol implemented a straight serial pass-through with Manchester (bi-phase) coding. A software state machine was used to continuously decode the output of the receiver, capturing any valid data and outputting it to the serial port. These transceivers allow a single vehicle communicate with one or more other vehicles during each transmission session, depending on distance of the receiving vehicles from the transmitting vehicle. Thus, inter-vehicle communication can be modeled as a sequence of one-to-some logical broadcast graphs. Ideally, each broadcast would be received by all other robots so the each session would have a star topology, but in reality, not all transmissions were received by all vehicles.

2.6. Experimental results

Performance of our communication and control algorithms was evaluated not only in simulation, but also in an existing 3D autonomous vehicle testbed at the University of Washington. The facility consists of three autonomous underwater vehicles linked by wireless communication (see previous section) and an instrumented water tank facility. The wireless communication was implemented via radio frequency with sensor data from a vision-based tracking system. During the past year, the tracking and communication system operational characteristics were determined. In implementation, this communication method can be constrained to emulate characteristics of a variety of environments and hardware.

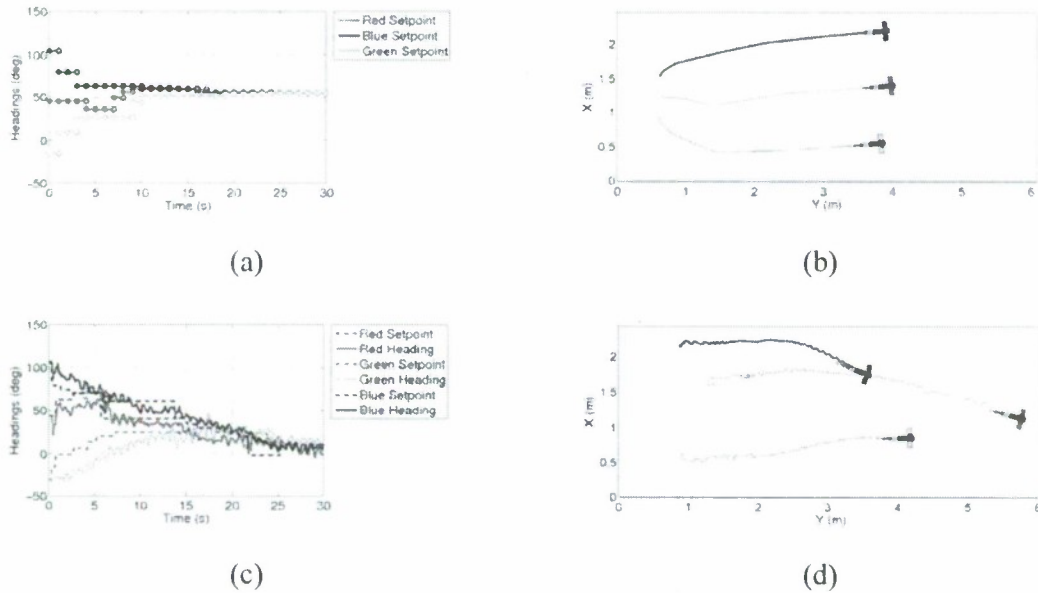


Figure 3: Simulation and experimental results for heading alignment with 50% packet loss. (a) Simulation of heading alignment signal; (b) overhead view of vehicle kinematics during heading control; (c) experimental onboard compass measurements during heading alignment; (d) external tracking of vehicle positions and heading during alignment experiment [5].

Results for a simple heading alignment task in both simulation and experiment are shown in Figure 3. The data transmission paths for the simulation duplicated what occurred in the experiment. As shown in the experimental results, the onboard sensors indicate that heading

alignment was achieved by the system; however, the external tracking system shows that the onboard magnetic compasses were biased by environmental noise. As the algorithm being run was based on the onboard sensor data, the results can be considered successful. Further, these results agree well with the simulation results in terms of time to convergence. Note that the oscillatory noise on the signal in the experiment is due to the fact that the robots locomote via an oscillating tail, and these oscillations are measurable by the compass. Similar results were achieved for additional experiments. An important point to note here is that the results were achieved even in this case where about half of the data packets were dropped. Upgrades to the RF transceivers have eliminated almost all of these dropped packets.

3. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the key accomplishments of the work in this project were the development of coordinated control algorithms for nonlinear systems with discrete time communication events and the evaluation of network topology energy efficiency for these algorithms relative to the discretization interval and data transfer rate. The results were demonstrated in both theory and in hardware including scenarios with significant packet loss. Additional tasks of target tracking and estimation were also considered as part of the project. Overall, the methodology and results have provided new insight and techniques for networked autonomous systems, and the results should have wide applicability in a range of multi-agent problems.

Journal Publications

1. "Resource Allocation in OFDMA with Time-Varying Channel and Bursty Arrivals," S. Kittipiyakul and T. Javidi, *IEEE Communications Letters*, **11**(9):708-710, Sep. 2007.
2. "Optimal Operating Point for MIMO Multiple-access Channel with Bursty Traffic," S. Kittipiyakul and T. Javidi, *IEEE Journal on Selected Areas in Communication*, **26**(12):4464-4474, Dec. 2007.
3. "Integration of Communication and Control Using Discrete Time Kuramoto Models for Multivehicle Coordination over Broadcast Networks," D. J. Klein, P. Lee, K. A. Morgansen, and T. Javidi, *IEEE Journal on Selected Areas in Communication*, **26**(4):695-705, May 2008.
4. "Delay Optimal Transmission Policy in a Wireless Multi-Access Channel," N. Ehsan and T. Javidi, *IEEE Transactions on Information Theory*, **54**(8):3745-3751, Aug. 2008.
5. "Network Coding Games with Unicast Flows," J. Price and T. Javidi, *IEEE Journal on Selected Areas in Communications*, **26**(7):1302-1316, Sep. 2008.
6. "Cooperative Estimation for Coordinated Target Tracking in a Cluttered Environment," B. I. Triplett, D. J. Klein and K. A. Morgansen, to appear in *ACM/Springer Mobile Networks and Applications Journal (MONET)*, (invited—special issue).
7. "High-SNR Analysis of Outage-Limited Communications with Bursty and Delay-Limited Information," S. Kittipiyakul, P. Elia, and T. Javidi, to appear in *IEEE Trans. on Info. Theory*.

Peer-reviewed conference proceedings

(available at <http://vger.aa.washington.edu/publications.html> or http://circuit.ucsd.edu/~tjavidi/index_files/publications.html)

1. "Cooperative Diversity in Wireless Networks with Stochastic and Bursty Traffic," P. Elia, S. Kittipiyakul and T. Javidi, *International Symposium Information Theory*, 2007.
2. "Distributed Estimation for Coordinated Target Tracking in a Cluttered Environment," B. I. Triplett, D. J. Klein, and K. A. Morgansen, *ROBOCOMM*, 2007.
3. "Integration of Communication and Control Using Discrete Time Kuramoto Models for Multivehicle Coordination over Broadcast Networks," D. J. Klein, P. Lee, K. A. Morgansen and T. Javidi, *Proc. 2007 IEEE Conference on Decision and Control*.
4. "Autonomous Underwater Multivehicle Control with Limited Communication: Theory and Experiment," D. J. Klein, P. K. Bettale, B. I. Triplett and K. A. Morgansen, *Proc. Second IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles*, 2008.
5. "Set Stability of Phase-Coupled Agents in Discrete Time," D. J. Klein and K. A. Morgansen, *Proc. American Control Conference*, 2008.

MS and PhD theses

(available at <http://vger.aa.washington.edu/publications.html> or http://circuit.ucsd.edu/~tjavidi/index_files/publications.html)

1. D. J. Klein. Coordinated Control and Estimation for Multi-Agent Systems: Theory and Practice. PhD Thesis, Department of Aeronautics and Astronautics, University of Washington, 2008.
2. B. I. Triplett. Multiple Vehicle Coordination and Cooperative Estimation for target Tracking with Applications to Autonomous Underwater Vehicle Systems. PhD Thesis, Department of Aeronautics and Astronautics, University of Washington, 2008.

3. P. K. Bettale. Design of a Reliable Embedded Radio Transceiver Module with Applications to Autonomous Underwater Vehicle Systems. Master's Thesis, Department of Electrical Engineering, University of Washington, 2008.

Personnel supported

- Kristi A. Morgansen (faculty, UW, PI)
- Tara Javidi (faculty, UCSD, CoPI)
- Petros Elia (postdoc, UCSD): Oct 2006-Jun 2007. Developed wireless networking tools.
- E. Ardestanizadeh (graduate student, UCSD): Oct 2007-Mar 2008. Developed algorithms for wireless communication.
- Patrick Bettale (graduate student, UW): Jan 2008-May 2008. Developed radio frequency transceiver.
- Daniel J. Klein (graduate student, UW): Oct 2005-Jun 2007. Developed algorithms for nonlinear coordinated control.
- Phillip S. Lee (graduate student, UCSD): Jul 2007-Mar 2008. Developed communication cost evaluation for coordinated control.
- Kudah Mushambi (graduate student, UW): Jun 2005-Sep 2005. Developed initial coordinated control algorithms.
- Jennifer Price (graduate student, UCSD): Apr 2007-Sep 2007. Developed methods for network coding.
- Benjamin I. Triplett (graduate student, UW): Oct 2007-Jan 2008. Developed coordinated tracking algorithms.
- Levi Gable (undergraduate student, UW): July 2007-Dec 2007. Assisted in experiments.
- Timothy La Fond (undergraduate student, UW): Oct 2006. Assisted in experiments.

Awards

- IEEE Senior Member, Kristi A. Morgansen—awarded April 2006.

AFRL Point of Contact

- Johnny Evers, AFRL/MNGN, Eglin AFB, FL, Phone 850-883-1887. Met at the University of Washington April 20, 2006, at the 2007 American Control Conference July 12, 2007, and at the 2007 Conference on Decision and Control.

Transitions

- None.

New Discoveries

- Licensing and copyright of the RF transceiver developed in part of this project are underway at the University of Washington through the Office of Technology Transfer.

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- [4] D. J. Klein and K. A. Morgansen, "Set Stability of Phase-Coupled Agents in Discrete Time," in *Proceedings of the American Control Conference*, 2008.
- [5] D. J. Klein, P. K. Bettale, B. I. Triplett and K. A. Morgansen, "Autonomous Underwater Multivehicle Control with Limited Communication: Theory and Experiment," *Proc. Second IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles*, 2008.