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Robust Architecctures For Complex Multi-Agent Heterogeneous Systems

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14. ABSTRACT

The research accomplished within this time period leveraged the prior accomplishments in the area of networked multi-agent systems. The past work (prior to 2011) focused on development of cooperative control algorithms in the presence of temporal and spatial constraints. During 2011-2014, we enriched the framework by i) developing cooperative control algorithms in the presence of dynamic information flow and quantized measurements [1], ii) developing a cooperative trajectory generation framework with account of spatial and temporal constraints [2], and iii) developing a decoupled architecture for distributed control of uncertain networked systems [3]. Additionally, a preliminary collision avoidance algorithm has been developed for a team of cooperating Unmanned Aerial Vehicles (UAV), executing a time-critical mission while encountering a non-cooperative aircraft.

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Robust Architectures for Complex Multi-Agent Systems

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FINAL REPORT

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Abstract: The research accomplished within this time period leveraged the prior accomplishments in the area of networked multi-agent systems. The past work (prior to 2011) focused on development of cooperative control algorithms in the presence of temporal and spatial constraints. During 2011-2014, we enriched the framework by i) developing cooperative control algorithms in the presence of *dynamic information flow* and *quantized measurements* [1], ii) developing a *cooperative trajectory generation* framework with account of spatial and temporal constraints [2], and iii) developing *a decoupled architecture* for distributed control of uncertain networked systems [3]. Additionally, a preliminary collision avoidance algorithm has been developed for a team of cooperating Unmanned Aerial Vehicles (UAV), executing a time-critical mission while encountering a non-cooperative aircraft.

Main accomplishments: The conceptual architecture of the cooperative control framework is depicted in

Figure **1**. The block diagram shows the interaction between the essential components of the architecture, such as the *Distributed Trajectory Generation*, *Collision Avoidance*, *Time Coordination*, and *Path Following* algorithms. The vehicles are exchanging information over a supporting communications network.

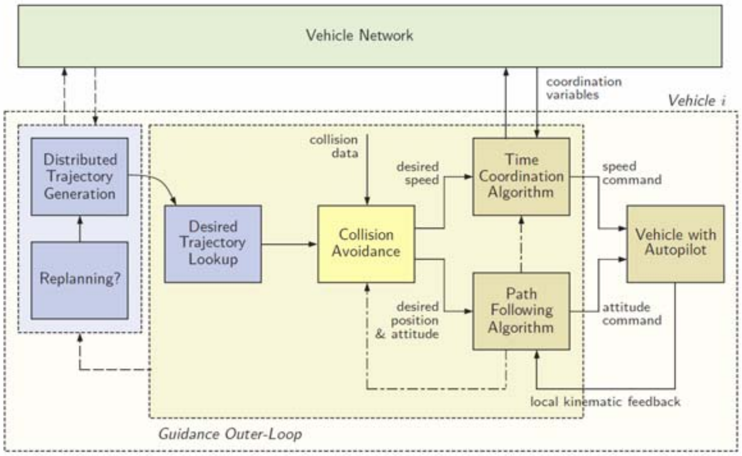

Figure 1 Cooperative Control Framework.

Several advances in these key components have been made over the reporting period. In particular, the convergence properties of a proportional-integral protocol for coordination of a network of agents with dynamic information flow and quantized measurements have been derived, when each agent is only required to exchange its coordination state with its neighboring agents, and the desired reference rate is only available to a group of leaders, [1]. The convergence of the collective dynamics is shown, when the graph that captures the network topology is not connected during some interval of time or even fails to be connected at all times. Lower bounds on the convergence rate of the collective dynamics as a function of the number of leaders and the Quality of Service (QoS) of the network are derived, which represent a measure of the level of connectivity of the dynamic graph that captures the underlying network topology. The convergence properties of the collective dynamics under quantized feedback are analyzed, where the solutions are interpreted in Krasovskii sense. We showed that in a fully quantized system one can afford much coarser quantization rate than in a partially quantized system.

In terms of algorithms for cooperative trajectory generation, Bézier curves have been explored and found useful for accommodating spatial deconfliction constraints. The *Gilbert-Johnson-Keerthi* algorithm (for computation of the minimum distance between convex shapes) along with *de Casteljau* algorithm (for subdividing the curve) have been explored for iteratively converging to the points on two Bézier curves that define the minimum distance in between them, [2]. Rational Bézier curves with tuning weights have been explored to accommodate more mission-specific constraints, and new subdivision points have been proposed that show faster convergence rates in determining the minimum distance between curves involving rational Bézier curves. Preliminary results show that using Bezier curves for the generation of feasible trajectories for a team of cooperating UAVs, result in more computationally efficient algorithms that may lend themselves for (near) real-time generation of these trajectories onboard the vehicles in the near future.

Design of collision avoidance algorithms, partly in support of the national effort in the safe integration of small UAVs in the National Airspace Systems, is also one of the main efforts within the development of this cooperative control framework. Results are obtained for a team of cooperating UAVs, avoiding a non-cooperating vehicle that is obstructing the area of operation and hampering the progress of the mission. It is shown that through speed adjustments of the collective team of UAVs, the non-cooperating vehicle is successfully avoided while ensuring coordination at all times. Hence, inter-vehicle collisions are prevented and the UAVs are able to successfully execute the mission and meet the critical time constraints. The results of this part of the research are reported in [4].

We also developed a control architecture that enables decoupling of the design of a robust controller with the communication protocol to the maximum extent, even in the presence of physical interconnections, [3]. With this architecture, one can integrate the existing communication protocols and robust control techniques into a unified system without worrying about the coupling between the control loop and the communication protocol.

Although all communication models can be integrated into this framework, we choose decentralized event-triggering model as an example to demonstrate the performance of the proposed architecture. Stability conditions have been derived for the resulting closed-loop systems in terms of communication and control parameters. Moreover, we showed that the transient performance of the communication-limited, uncertain system can be rendered arbitrarily close to a reference model by tuning the bandwidth of the low-pass filter in the local robust controller. The reference model in turn can be arbitrarily close to an ideal mathematical model, given sufficient communication resources.

Other theoretical results that may find their application in the overall cooperative control framework, are the developments of a real-time implementation of output-feedback L_1 adaptive controller over real-time networks [5], and an L_1 Simplex enabling fault-tolerant control of Cyber-Physical Systems [6]. In the development of an output-feedback L_1 adaptive controller over real-time networks, the system under consideration is networked with transmission delays, and it contains unmatched nonlinear uncertainties. We use event-triggering to trigger data transmissions from the plant (controller) to the controller (plant). An output-feedback strategy is provided based on the L_1 adaptive control architecture [7]. Stability conditions were derived, which establish the tradeoff between the control performance and the QoS of the communications network. We also derived the performance bound on the difference between the states in the uncertain networked control system and a stable ideal model, in terms of the event thresholds, the allowable transmission delays, and the adaptation rate. This bound can be further reduced by improving the QoS, which means that the performance of the uncertain system is subject to the hardware limitations.
The development of the L_1Simplex addresses the concerns regarding system failures that comprise of physical failures as well as software failures. As the complexity of Cyber-Physical Systems (CPS) increases, it becomes more and more challenging to ensure the reliability of CPS, especially in the presence of system failures. Simplex architecture is shown to be an efficient tool to address the software failure in such systems. However, when physical failures also appear, Simplex does not work anymore because the physical dynamics change due to physical failures. The Simplex architecture designed for the original physical model may not be suitable for the new dynamics. To address both software and physical failures, the L1Simplex architecture was developed, which contains the safety monitor, the high-performance controller (HPC), the L_1-based high-assurance controller (HAC), and the decision logic for controller switching. The safety monitor is used to monitor the system behavior. It leads to another controller switching rule besides the stability-envelope-based rule in the decision logic. The HAC is designed based on the L_1 adaptive controller. With this HAC, the stability envelope is computed, which can be further extended by using multiple controllers in the HAC module. We showed that the L_1 Simplex architecture can efficiently handle a class of software and physical failures.

We leveraged NASA funding in the area of integration of UAVs into National Airspace Systems, which provides appropriate opportunity to transition the basic research results obtained within our AFOSR grant.

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Honors

2014	TUM-IAS honorary **Hans Fischer senior fellow**
2014	**Humboldt prize**, Alexander von Humboldt Foundation, Germany
2014	**Keynote speaker**, International Conference on Unmanned Aircraft Systems, Orlando, FL
2013	**Plenary speaker**, II Midwest Control and Game Workshop, University of Notre Dame, IN
2012	**Technical Achievement Award**, World Congress, 9th International Conference on Mathematical Problems in Engineering, Aerospace and Sciences, Vienna, Austria
2012	**Best Presentation Award**, AIAA Guidance, Navigation and Control Conference
2012	**Keynote speaker**, ICNPAA World Congress: Mathematical Problems in Engineering, Sciences and Aerospace, Vienna, Austria
2011-2014	**University Scholar**, UIUC
2011 - 2012	Member of Engineering Faculty Leadership Forum of UIUC
2011	**AIAA Mechanics and Control of Flight Award**, with the citation “*For ground breaking work in L_1 robust adaptive control of nonlinear uncertain systems, vision-based guidance, navigation and control, and cooperative path planning of UAVs*”

2011 **Semi-Plenary speaker**, Chinese Control and Decision Conference, Mianyang, China

Transitions

- Raymarine has successfully implemented L_1 Adaptive Control on their Evolution Autopilot series for marine vessels.
- Unmanned Dynamics multirotor solutions (educopters acquired by US Universities, phocopters acquired by Naval Air Warfare Center Weapons Division)
- The theory has been implemented on NASA’s AirSTAR GTM dynamically scaled jet powered piloted aircraft and flight tested for post-stall flight regimes. POC: I. Gregory, NASA LaRC, Hampton, VA 23681, Ph: 757-864-4075, E-mail: i.m.gregory@larc.nasa.gov.
- The theory has been used to augment an existing autopilot (Piccolo) for accurate path following in the problem of time-critical cooperation of UAVs with spatial constraints in the presence of time-varying communication network topology. POC: Isaac Kaminer, MAE, NPS, Monterey, CA 93943, Phone: 831-656-3459 (further transition to USSOCOM in TNT exercises).

New Discoveries

2014, Feb. 9 Patent (control No.13/023,965) “Adaptive Control for Uncertain Nonlinear Multi-Input Multi-output Systems” (with C. Cao and E. Xargay)