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Cooperation and Autonomy in Communication-Limited Environments

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14. ABSTRACT
A framework is developed that offers novel distributed trajectory-planning and online time-critical coordination capabilities for a fleet of cooperating vehicles that communicate over a lossy wireless network. A distributed algorithm is developed that balances the trajectory-planning workload among all agents in the fleet. The resulting algorithm combines tools from nonlinear optimization and distributed programming, and leverages the polynomial structure of the trajectories and the differential flatness property of the system dynamics to compute the subdifferential analytically. As compared to the existing bundle methods the computational cost is significantly reduced. Regarding time-critical coordination, the temporal specifications and the coordination capabilities of the vehicles have been broadened significantly to accommodate the diversity of constraints required in realistic missions of interest to defense operations. The distributed time-critical coordination law lets the vehicles adjust their speed in real time to meet the desired temporal and coordination constraints in the presence of external disturbances. This research introduced a new classification of these constraints that has led to significant improvement inflexibility, agility and adaptability of the planned missions.

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Cooperation and Autonomy in Communication-Limited Environments

FA9550-15-1-0518

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Abstract

A framework is developed that offers novel distributed trajectory-planning and online time-critical coordination capabilities for a fleet of cooperating vehicles that communicate over a lossy wireless network. A distributed algorithm is developed that balances the trajectory-planning workload among all agents in the fleet. The resulting algorithm combines tools from nonlinear optimization and distributed programming, and leverages the polynomial structure of the trajectories and the differential flatness property of the system dynamics to compute the subdifferential analytically. As compared to the existing bundle methods the computational cost is significantly reduced. Regarding time-critical coordination, the temporal specifications and the coordination capabilities of the vehicles have been broadened significantly to accommodate the diversity of constraints required in realistic missions of interest to defense operations. The distributed time-critical coordination law lets the vehicles adjust their speed in real time to meet the desired temporal and coordination constraints in the presence of external disturbances. This research introduced a new classification of these constraints that has led to significant improvement in flexibility, agility and adaptability of the planned missions. Moreover, tools from Lyapunov stability, switched systems, and algebraic graph theory were leveraged to derive transient and steady-state performance bounds for some of the new time-critical coordination strategies.

The research over the past three years addressed theoretical topics of practical importance in the field of autonomy for multi-agent systems. This effort aimed to expand the capabilities of the system architecture [1]–[3], depicted in Figure 1, to bridge the gap between theory and application, expand the flexibility of the framework to a larger class of missions, and adapt to the growing complexity demanded of cooperating agents [4], [5]. This framework is based on two fundamental ideas: i) decoupling space and time to ensure vehicles can track their paths regardless of their speed profile, as long as it is physically feasible, and ii) the compartmentalization of each task within the framework — trajectory-generation, path-following, time coordination, and vehicle stabilization — so that different algorithms and technologies can be swapped with ease [6]. This compartmentalization and space-time decoupling allows the higher-level algorithms, such as time-coordination, to abstract away from the vehicle dynamics, which

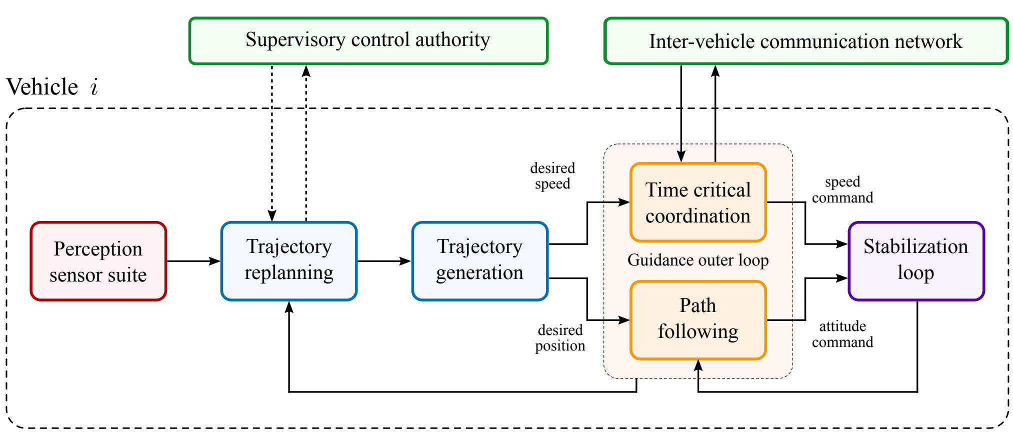


Fig. 1: Architecture of the time-critical coordination framework.

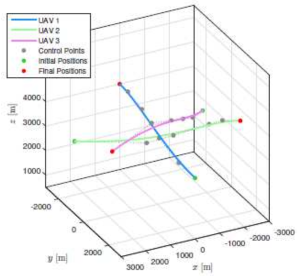
allows for the design of more elaborate time-coordination laws that adapt to the demanding complexity with known guarantees [7], [8]. In particular, this effort sought to advance the state-of-the-art in motion control and planning of distributed systems through two different thrusts: distributed cooperative trajectory generation, and coordination in communication-limited environments. The next section contains a brief summary of the advances achieved in the aforementioned thrusts through this research effort.

I. Status of the Effort

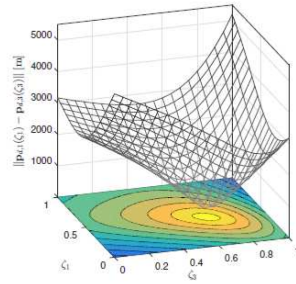
- **Cooperative trajectory generation for time-critical missions**: broadened the funcitonality and efficiency of the trajectory generation blocks in Figure 1, and was divided into two main milestones. First, a centralized framework for the generation of spatial trajectories for a team of cooperative vehicles was developed [9]–[11]. The proposed approach leveraged the polynomial structure of the curves for both space and time to avoid discretization, and improve scalability, while ensuring that all trajectories are collision free either through spatial separation or temporal deconfliction. Moreover, the differential flatness properties of the vehicle dynamics where exploited to efficiently guarantee that the dynamic constraints of the agents are also met. The efficacy of the centralized cooperative trajectory generation framework was evaluated through two different simulation scenarios that included fixed-wing aircraft and multirotors. The second milestone of this thrust focused on distributing the trajectory generation framework over the different vehicles in the network [12], [13]. This was posed as a semi-infinite programming problem, which is inherently non-smooth. However, the polynomial structure of the trajectories — both in time and space — was leveraged to reformulate it as an ordinary (finite-dimensional) non-smooth optimization problem. A distributed bundle method was proposed to solve this class of problems, where the polynomial structure of the trajectories was exploited to obtain the entire subdifferential of the non-smooth functions. The resulting algorithm combines tools from non-smooth optimization, in particular bundle methods, and distributed nonlinear programming methods. Another contribution of this effort was the computation of the whole subdifferential, hence avoiding the complicated line search procedure characteristic of bundle methods [13]. As a result, the termination criteria for this algorithm becomes intuitive and straightforward as opposed to the stopping criteria for existing bundle methods. Figures 2 and 3 illustrate these results.

(a) Transmission at step r (b) Transmission at step r'

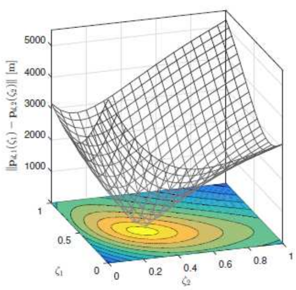
Fig. 2: Two-step communication model for the exchange of the states of the optimization problem c_i and c_i'. As the vehicles indirectly require information from vehicles in the network that do not share a direct communication link, a two-step information exchange protocol is proposed. Although this is not common practice for existing distributed (optimization) algorithms, it is still a relaxed requirement compared to a communication topology that is complete, or a routing protocol that uses multi-hops so that an agent can send a package of information to any other agent in the network, even if they are not neighbours.



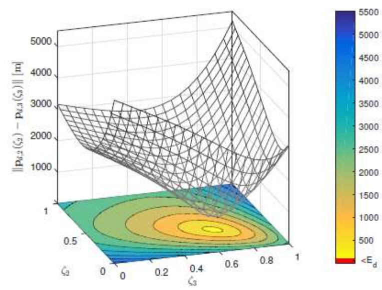
(a) Three-dimensional flight paths



(b) Path separation UAV 1 and 2



(c) Path separation UAV 1 and 3



(d) Path separation UAV 2 and 3

Fig. 3: Three-dimensional trajectories for a team of three cooperating UAVs. The trajectories are guaranteed to be collision free through spatial separation. This set of trajectories were computed using the aforementioned distributed algorithm, and the communication protocol depicted depicted in Figure 2.

- **Coordination in communication-limited environments**: novel time-critical coordination strategies were developed to capture the coordination and temporal constraints required to perform realistic missions with multiple assets. These new coordination strategies were able to automate procedures that are often controlled by human operators time criticality, while addressing time-criticality and the growing complexity envisioned for multi-vehicle scenarios. The novel classification of temporal and coordination constraints, depicted in Figure 4, lead to the six different coordination strategies, illustrated through six different missions. The usability of the resulting coordination constraints can be summarized as follows:
  - **Tight coordination**: forces the vehicles to strictly observe their coordination constraints, and drives the inter-vehicle coordination error to zero. This type of coordination is typical of scenarios, where maintaining the desired relative position among vehicles is crucial. A common example is represented by close proximity operations as shown in Figure 4 through the airshow and aerial refueling scenarios. In addition, tight coordination can be leveraged to ensure vehicles do not violate the minimum safety distance separation when assigned time-deconflicted trajectories.
  - **Loose coordination**: defines an allowable margin of error in the coordination among vehicles, and ensures that the inter-vehicle coordination error converges to a Δ_c-neighborhood of zero. Naturally, loose coordination is a relaxation of tight coordination specifications. Loose coordination constraints are common in mission scenarios where coordination is still utilized to ensure inter-vehicle separation, but mid to far distance operations provide a safety margin in the coordination realm, as depicted in Figure 4.

  Similarly, the possible types of temporal constraints can be applied as follows:
  - **Unenforced temporal constraints**: do not impose any temporal specifications on the vehicles. This type of temporal constraint is used in missions that do not require the specification of an

arrival time or arrival window at any point along the paths of the vehicles. In scenarios with unenforced temporal constraints, the reference agent is typically not a member of the fleet, but a supervisory control facility that dictates the pace of the mission. Two examples that illustrate the use of unenforced temporal constraints are depicted in Figure 4.

- **Strict temporal constraints**: force the leaders to precisely observe their temporal specifications. This type of constraint is characteristic of missions that require the vehicles to be at one or more specific points along their paths at a particular moment in time. Again, two scenarios that illustrate the use of strict temporal constraints in real-world applications are shown in Figure 4.
- **Relaxed temporal constraints**: provide the vehicles with an allowable margin of error in their temporal specifications. Relaxed temporal constraints must be imposed in missions that require the vehicles to reach one or more points along their paths within a temporal window. Figure 4 presents two scenarios where relaxed temporal constraints are necessary to automate the mission.

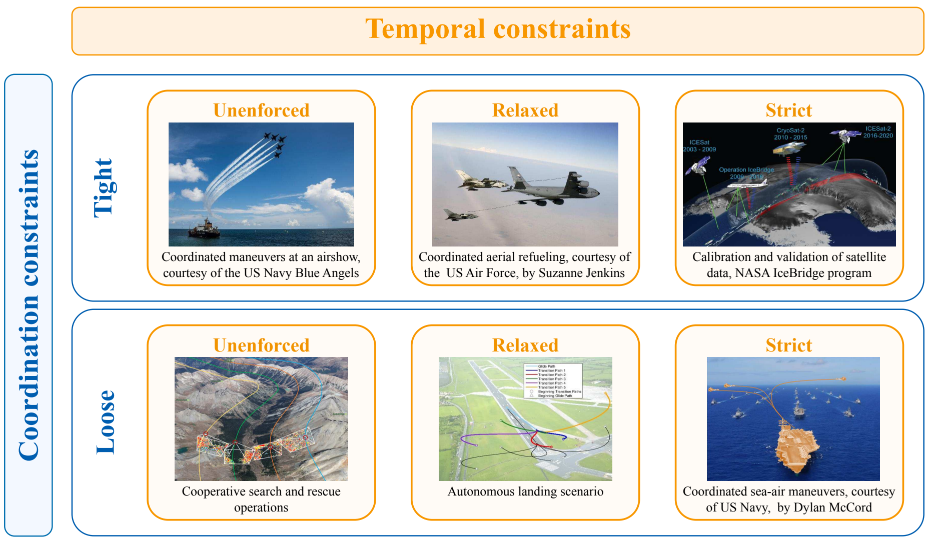
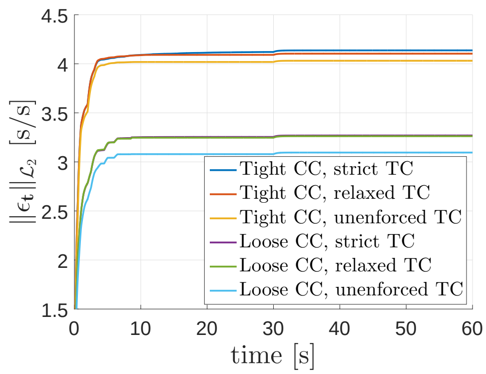


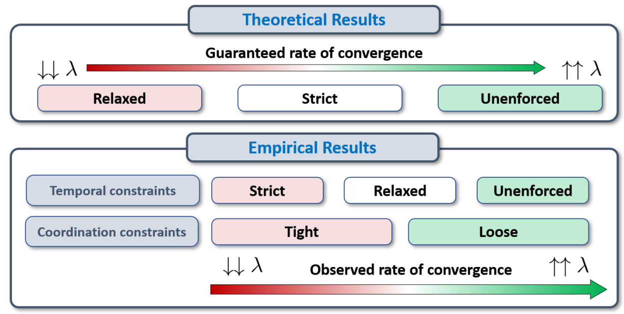
Fig. 4: Time-critical coordination strategies and illustrative missions that could be implemented using the coordination strategies developed.

In addition, an agent-specific coordination strategy was theorized to encompass those missions where each vehicle may behave differently with respect to different agents. As a result, the agent-specific strategy may combine all the possible strategies in Figure 4 into a single mission. Lyapunov stability, hybrid systems, and algebraic graph theory were leveraged to derive performance bounds for the transient and steady-state responses for tight coordination under a persistently exciting network topology. The convergence rate and control effort of the networked dynamical systems for unenforced, relaxed, and strict temporal constraints were compared theoretically through their lower bounds, and experimentally through Monte Carlo simulations. The conclusions of these results are shown in Figure 5. In addition, earlier work on estimation-based consensus protocols was further expanded. New estimation dynamics were derived to improve the convergence rate of the coordination errors. Different tools from network topology control were leveraged to ensure that only the coordination states from useful network estimators were included in the consensus protocol. These newly formulated consensus protocols were then evaluated across a wide range of quality of service (QoS) through simulations. To evaluate the efficacy of these algorithms, new local and global measures that characterize the activity of the estimators were proposed, as well as a realizable measure of the transient performance of the fleet. The results of this research are summarized in Figure 6.

Both the distributed cooperative trajectory generation and the time-critical coordination algorithms were designed to integrate seamlessly with the path-following and inner stabilization loop depicted in Figure 1.



(a) Truncated $\mathcal{L}_2$ norm of the control effort



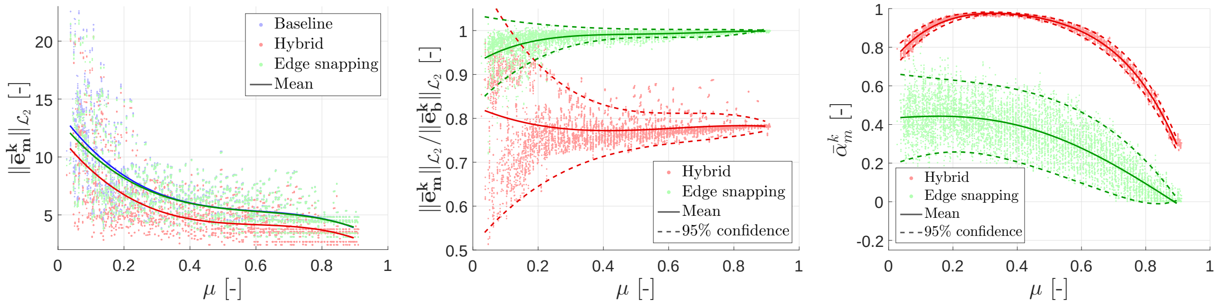
(b) Comparison of the theoretical and empirical results on the guaranteed rate of convergence.

Fig. 5: Control effort and guaranteed rate of convergence for the time-critical coordination strategies in Figure 4. Figure 5a shows the truncated $\mathcal{L}_2$ norm of the control effort for the same simulation scenario with 5 vehicles run for all strategies. Tight coordination significantly increases the control effort as compared to loose coordination. The same tendency can be observed as one imposes stricter temporal constraints, although the difference is more subtle. Figure 5b highlights the effect of coordination and temporal constraints on the convergence rate. In this case, experimental results show that the more strict these constraints are, the smaller the observed rate of convergence is. However, theoretical results show that the guaranteed rate of convergence for relaxed temporal constraints is smaller than for strict temporal constraints. This is due to the conservatism of in the proof for relaxed temporal constraints caused by the variability in the coordination link weights. These results do not conflict with the experimental results since the theoretical results only provide a lower bound on the rate of convergence.

II. Technology Transitions

The Advanced Controls Research Laboratory has continuously pursued the transition of the system architecture shown in Figure 1, and the theoretical guarantees of the algorithms developed to various applications, leveraging additional funding sources for that. Among the different technology transitions accomplished in the past three years, the following are of special relevance to AFOSR:

- **NASA LaRC Autonomy Incubator:** The time-critical coordination laws for tight coordination have been partially implemented for a fleet of small Unmanned Aerial Vehicles that communicate over a wireless communication network. The distributed algorithms use a Data Distribution Service (DDS) protocol that complies with military requirements, offers great flexibility from a software development perspective, and incorporates tools to monitor and modify the QoS of the communication network. In this case, the time-critical coordination algorithms were combined with a silhouette-informed trajectory planning algorithm [14], that sought to expand the set of geometric tools available for trajectory-planning in cluttered examples. This would not have been possible without the modularity that the system architecture in Figure 1 presents.
- **US Edwards Air Force Base:** An inner stabilization loop designed for easy integration with the remaining blocks of the framework shown in Figure 1 was designed for a Calspan's Learjet aircraft [15], [16]. However, in this case the attitude and speed commands were provided by a pilot, instead of a path-following and time-critical coordination algorithms as depicted in Figure 1. The stabilization loop consisted of a baseline controller designed to meet Level 1 requirements as specified by MIL-STD-1797. The baseline was then augmented with an $\mathcal{L}_1$ adaptive controller with a piecewise-linear adaptation law that provides robust performance behavior in the presence of disturbances. The



(a) $\mathcal{L}_2$-norm of the average coordination error

(b) Normalized $\mathcal{L}_2$-norm of the average coordination error

(c) Average activity of estimators

Fig. 6: Monte Carlo simulation results, 6930 scenarios with 8 vehicles. Figure 6a confirms the strong dependence between the QoS and the transient response of the inter-vehicle coordination error, as anticipated by theory. The hybrid mean line in Figure 6a indicates that the hybrid approach consistently improves the transient response of the baseline protocol across a wide range of QoS. Nonetheless, the edge-snapping mean line shows smaller efficacy in improving the transient response. Figure 6b shows that all the points corresponding to the hybrid approach are below 1, which provides strong numerical evidence that this approach effectively improves the transient response across all QoS. However, in Figure 6b the confidence intervals of the hybrid approach are significantly wider in low connectivity scenarios. Note also that, 98.75% of the edge-snapping points are less than or equal to 1. This high percentage shows improved behavior in almost all simulation runs for the edge-snapping approach. Figure 6c shows that the estimation activity decreases at low and high network connectivity. This is consistent with the activation thresholds defined in the network topology control logic.

complete inner stabilization loop was tested for both landing and cruise configurations first through extensive simulations and later through flight tests. Initially, flight tests were performed for nominal conditions. Once the flight software passed the corresponding safety review, artificial failures were injected to evaluate the robustness and performance in the presence of off-nominal dynamics such as engine failure, a shift in the center of mass, and a lateral phugoid among other examples.

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III. Selected Publications Complementary to References Above

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1) Javier Puig-Navarro, PhD student.
2) Arun Lakshmanan, PhD student.
3) Venanzio Cichella, PhD student, graduated spring 2018 and joined University of Iowa as faculty.
4) Ronald Choe, PhD student, graduated spring 2017 and moved to Singapore.
5) Naira Hovakimyan, Professor at the Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign.

VII. Honors and Awards

- Naira Hovakimyan was elevated to AIAA Fellow (2017) and IEEE Fellow (2018).
- Naira Hovakimyan got IEEE CSS award for Technical Excellence in Aerospace Controls (2017).
- Naira Hovakimyan got AIAA Pendray Aerospace Literature award (2019).
- Naira Hovakimyan got Society of Women Engineers Achievement award (2015).

VIII. AFRL Points of Contact

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IX. NASA Points of Contact

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- Irene Gregory: Irene.M.Gregory@nasa.gov.