# CAREER: Co-Design of Networking and Decentralized Control to Enable Aerial Networking in an Uncertain Airspace (May 2021)

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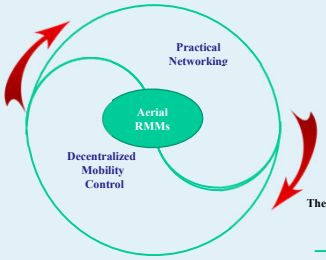
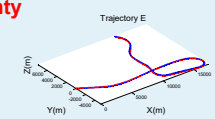
## Introduction

Airborne networking utilizes direct flight-to-to-flight communication for flexible information sharing, safe maneuvering, and coordination of time-critical missions. It is challenging because of the high mobility, stringent safety requirements, and uncertain airspace environment.

This project uses a co-design approach that exploits the mutual benefits of networking and decentralized mobility control in an uncertain heterogeneous environment. The approach departs from the usual perspective that views physical mobility as communication constraints, communication as constraints for decentralized mobility control, and uncertain environment as constraints for both. Instead, we proactively exploit the constraints, uncertainty, and new structures with information to enable high-performance designs.




**A comprehensive theoretical framework for Cyber-Physical Systems to exploit the mutual benefits of networking and decentralized control under uncertainty**




The core: Aerial RMMs

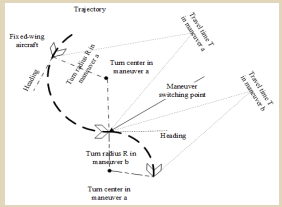
Uncertainty-exploiting decentralized control benefits networking

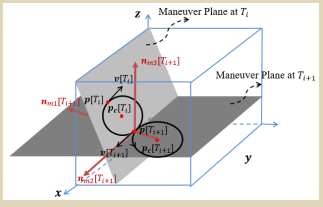
Practical networking to facilitate decentralized mobility control

The features of the co-design such as scalability, fast response, tractability, and robustness to uncertainty advance the core CPS science on decision-making for large-scale networks under uncertainty.

## UAV Random Mobility Models

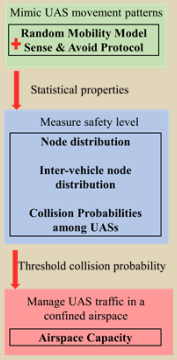
- We completed the development of both the 2-dimentioanl (2-D) and the 3-D smooth turn (ST) modeling framework for fixed-wing aircraft, which can serve as a design and evaluation foundation for future ANs.

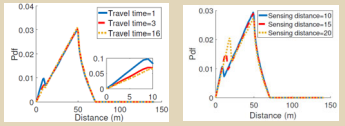


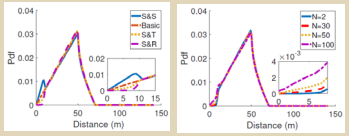

- By placing the random mobility models under the framework of random switching systems, we completed general online and offline estimation methods for these systems, using Expectation-Maximization and other methods.

- We equipped random mobility models with sense and avoidance protocols protocols to capture the flexible, variable, and uncertain movement patterns of UASs subject to separation safety constraints.
- We analyzed statistical properties including stationary location distribution and stationary inter-vehicle distance distributions, which leads to collision collision probability and airspace capacity for an airspace of dense UAV operations.



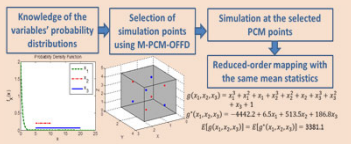

Impact of sensing distance and flexibility




Comparison of multiple sense and avoidance protocols

## Uncertainty Exploited Control

- We completed the development of scalable uncertainty evaluation method that breaks the curse of dimensionality in uncertainty evaluation. Published standalone Matlab tools for the general public to use this new uncertainty evaluation method.
- Built on the scalable uncertainty evaluation method that we developed in previous years, we completed the development of optimal control and reinforcement-learning based control for systems subject to high dimensional uncertainties.
- The solution was also extended to address the uncertainty quantification needs in dynamic graphical games and general random switching systems.



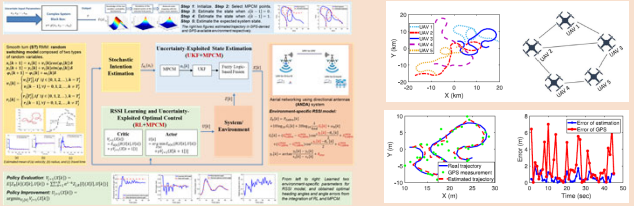

**System dynamics:** $\dot{x} = A(\alpha)x + \sum_{j=1}^{N} B_j u_j$

**Expected cost:** $J_i(x(0), u_i, u_{-i}) = E\left[\int_0^\infty r_i(x, u_i, u_{-i})dt\right]$

$$= E\left[\int_0^\infty x^T Q_i x + \sum_{j=1}^{N} u_j^T R_{ij} u_j \, dt\right]$$

**Value function:** $V_i(x(t)) = E\left[\int_t^\infty x^T Q_i x + \sum_{j=1}^{N} u_j^T R_{ij} u_j \, dt\right]$

**Optimal control policy:** $u_i^* = \underset{u_i}{\operatorname{argmin}} J_i(x(0), u_i, u_{-i})$

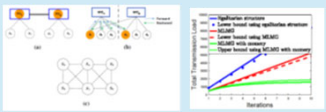


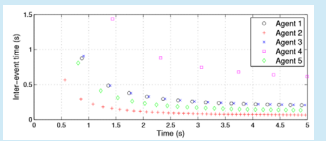




## Practical Networking to Facilitate Fast Decentralized Mobility Control

- We completed the development of layered structures to reduce data transmission load required to reach consensus for UAV networks.
- We developed event-triggered control with guaranteed lower bounds to reduce the communication and control cost.

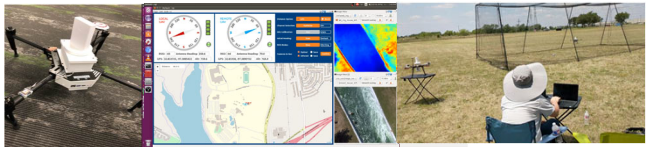



- We applied the event-triggered solution to graphical games.

## Testbed Development

- We enhanced the testbed of UAV-based on-demand communication system by redesigning the whole system in TX2 and improving the hardware and software endurance.
- We extended the capability to beyond visual line of control and other UAV applications.



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