CAREER: Co-Design of Networking and Decentralized Control to Enable Aerial Networking in an Uncertain Airspace (Year 4 Results)

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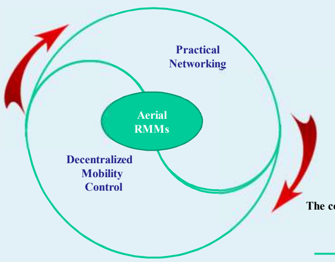
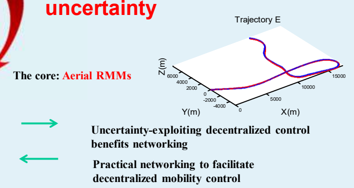
Introduction

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.



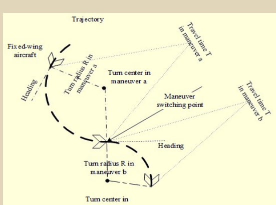
A comprehensive theoretical framework for Cyber-Physical Systems to exploit the mutual benefits of networking and decentralized control under uncertainty

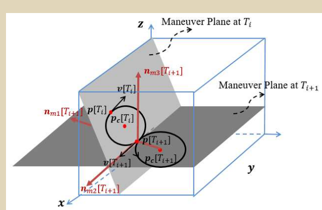


The features of the co-design such as scalability, fast response, tractability, and robustness to uncertainty advance the core CPS science on decision-making for large-scale networks under uncertainty.

UAV Random Mobility Models

In the year of 2018-2019, we completed 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.





Placing the random mobility models under the framework of random switching systems, we completed the online and offline Expectation-Maximization estimation methods for these systems.

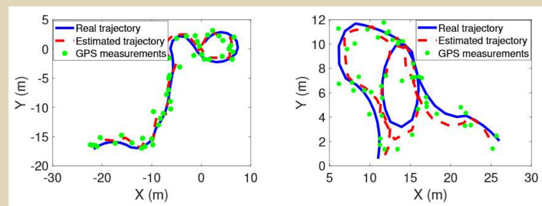
Type 1 random variables (RVs) describe the characteristics for each maneuver; type 2 RVs describes how often the switching of type 1 random variables occurs.

$$
\begin{aligned}
x_i[k+1] &= x_i[k] + v_i[k]\cos(\phi_i[k])\delta,\\
y_i[k+1] &= y_i[k] + v_i[k]\sin(\phi_i[k])\delta,\\
\phi_i[k+1] &= \phi_i[k] + \omega_i[k]\delta,
\end{aligned}
$$

$$
v_i[k] = \begin{cases} v_i[T_j^i], & \text{if } \exists j \in [0,1,2,..), k = T_j^i \\ v_i[k-1], & \text{if } \forall j = 0,1,2,.., k \neq T_j^i \end{cases}
$$

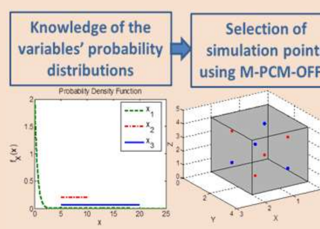
$$
r_i[k] = \begin{cases} r_i[T_j^i], & \text{if } \exists j \in [0,1,2,..), k = T_j^i \\ r_i[k-1], & \text{if } \forall j = 0,1,2,.., k \neq T_j^i \end{cases}
$$

We also completed the estimation of expected states of random switching systems by integrating an uncertainty evaluation method called multivariate probabilistic collocation method (MPCM) and unscented Kalman Filter (UKF). Steps 1 and 2 select initial conditions and MPCM points to initialize Steps 3-5; Step 3 and 4 find the state estimators based on switching or not; Step 5 finds the expected state by integrating the two estimators found in Steps 3 and 4.



Uncertainty Exploited Control

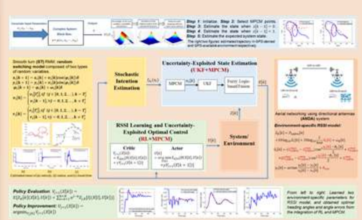
In the year of 2018-2019, we completed the M-PCM-OFFD to achieve an effective and scalable output statistics estimation. Beyond its use to stochastic optimal control that we developed last year, we further developed its use in stochastic switching systems, and dynamic games.



$$g(x_1,x_2,x_3) = x_1^3 + x_1^2 + x_1 + x_2^3 + x_2^2 + x_2 + x_3^3 + x_3^2 + x_3 + 1$$

$$g^*(x_1,x_2,x_3) = -4442.2 + 6.5x_1 + 513.5x_2 + 186.8x_3$$

$$E[g(x_1,x_2,x_3)] = E[g^*(x_1,x_2,x_3)] = 3381.1$$



System dynamics: $\dot{\boldsymbol{x}} = \boldsymbol{A}(\boldsymbol{a})\boldsymbol{x} + \sum_{j=1}^{N} \boldsymbol{B}_j \boldsymbol{u}_j$

Expected cost: $J_i(\boldsymbol{x}(0), \boldsymbol{u}_i, \boldsymbol{u}_{-i}) = E\left[\int_0^\infty r_i(\boldsymbol{x}, \boldsymbol{u}_i, \boldsymbol{u}_{-i}) dt\right]$

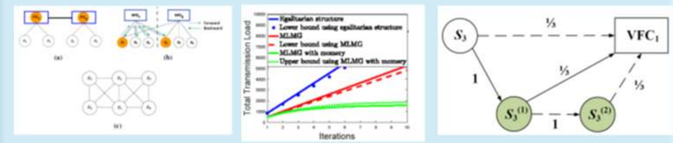
$$= E\left[\int_0^\infty \boldsymbol{x}^T \boldsymbol{Q}_i \boldsymbol{x} + \sum_{j=1}^{N} \boldsymbol{u}_j{}^T \boldsymbol{R}_{ij} \boldsymbol{u}_j \, dt\right]$$

Value function: $V_i(\boldsymbol{x}(t)) = E\left[\int_t^\infty \boldsymbol{x}^T \boldsymbol{Q}_i \boldsymbol{x} + \sum_{j=1}^{N} \boldsymbol{u}_j{}^T \boldsymbol{R}_{ij} \boldsymbol{u}_j \, d\tau\right]$

Optimal control policy: $\boldsymbol{u}_i^* = \underset{\boldsymbol{u}_i}{\operatorname{argmin}} J_i(\boldsymbol{x}(0), \boldsymbol{u}_i, \boldsymbol{u}_{-i})$

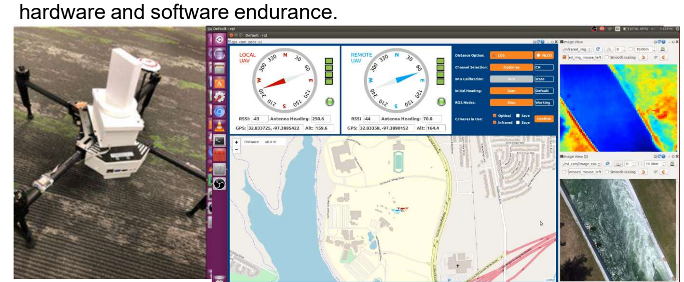
Practical Networking to Facilitate Fast Decentralized Mobility Control

Layered structures are more effective than equivalent egalitarian structures in terms of the data transmission load required to reach consensus for UAV networks. We completed analytical results on the asymptotic and transient performance when additional local memories are used to further reduce the data transmission load to reach consensus. We also studied the effect of delay.



Testbed Enhancement

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.



Some References

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