CAREER: Co-Design of Networking and Decentralized Control to Enable Aerial Networking in an Uncertain Airspace

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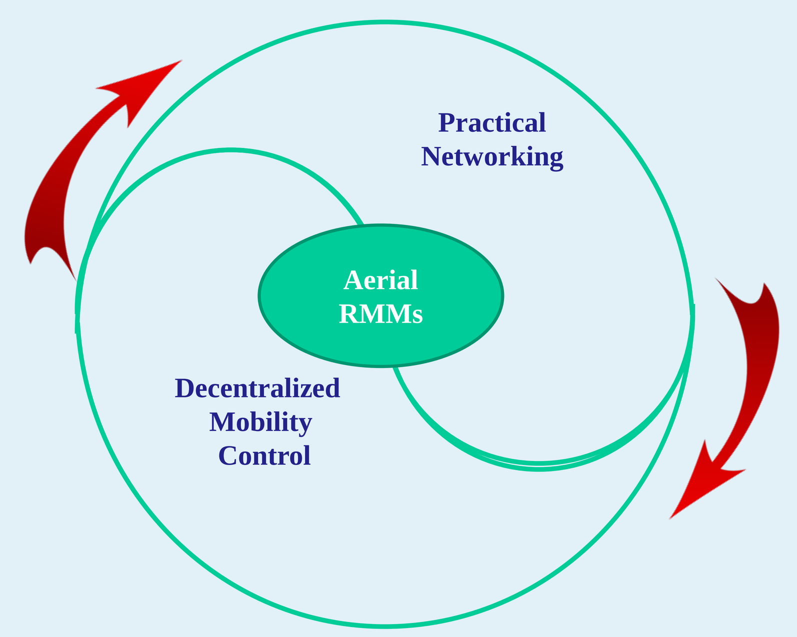
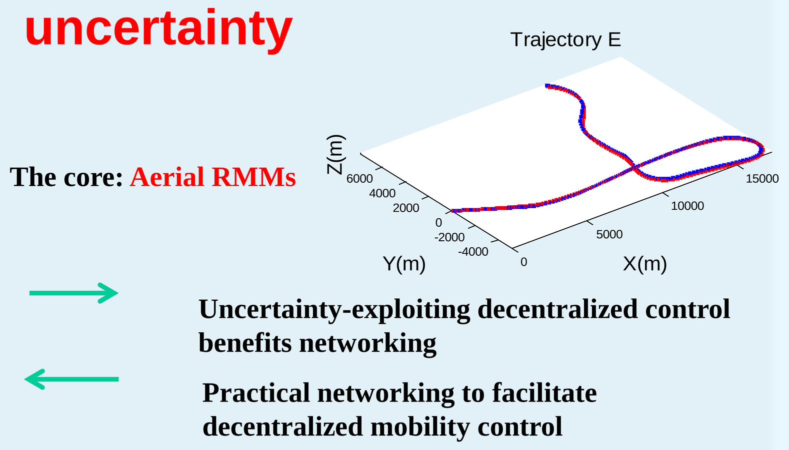
Introduction

Airborne networking utilizes direct flight-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.



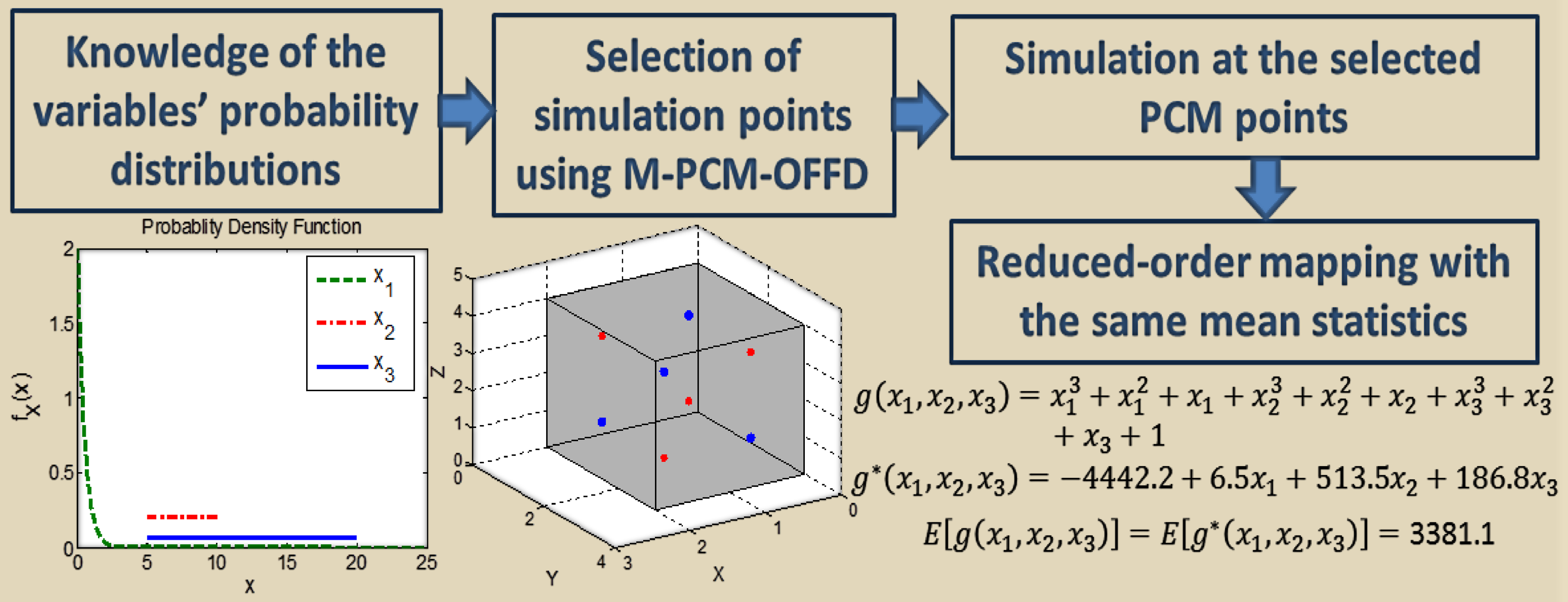
A comprehensive theoretical framework for Cyber-Physical Systems to exploit the mutual benefits of networking and decentralized control under uncertainty



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.

Uncertainty-Exploring Decentralized Mobility Control to Facilitate Networking

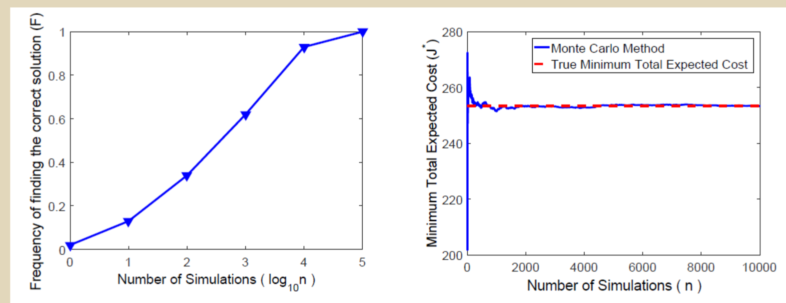
In the year of 2015-2016, we developed a systematic scalable uncertainty evaluation method that breaks the curse of dimensionality. The method integrates MPCM and Orthogonal Fractional Factorial Design (OFFD) to maximally reduce the number of simulations from from 2^{2m} to $2^{\lceil log_2(m+1) \rceil}$, for a system mapping of m parameters. We proved that the resulting reduced-size simulation set maintains the correct mean output estimation under broad assumptions that hold for realistic systems, and is the most robust to numerical errors among all subsets of the same size in the MPCM simulation set.



We also explored the capabilities of MPCM and MPCM-OFFD based stochastic optimal controls for three cases with increasing complexity level: 1) time-invariant uncertain parameters, 2) time-varying uncertain parameters independent across time, and 3) time-varying uncertain parameters with the dependency defined by Markov chains. The analyses and simulation results illustrate the efficiency and consistency of these two approaches.

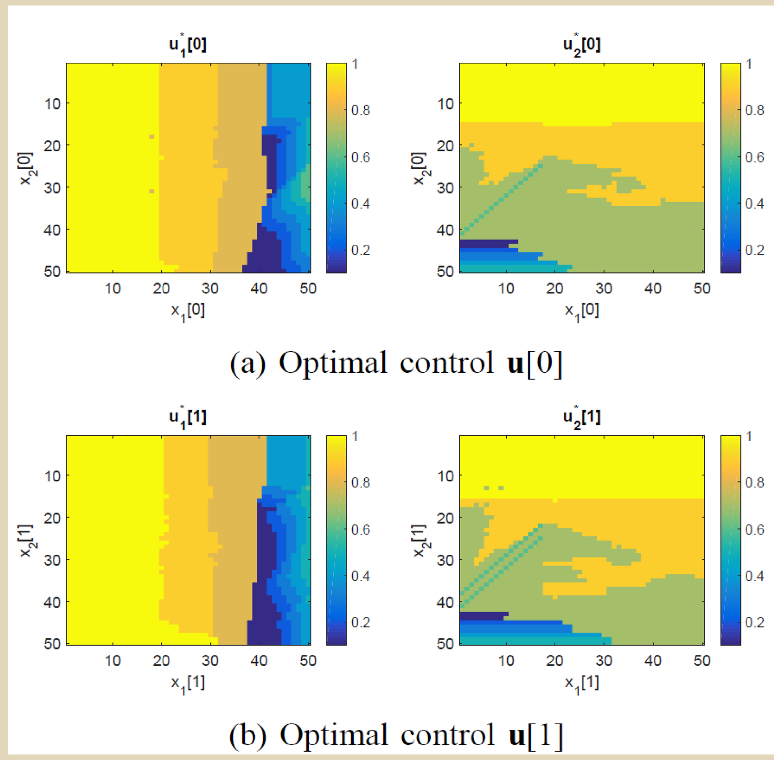
Number of samples (n)	Optimal control found (u^*)	Minimum mean cost ($J'^*(x[0])$)
2	3.6	248.1923
3	3.6	253.1802
4	3.6	253.3476
5	3.6	253.3491
6	3.6	253.3491

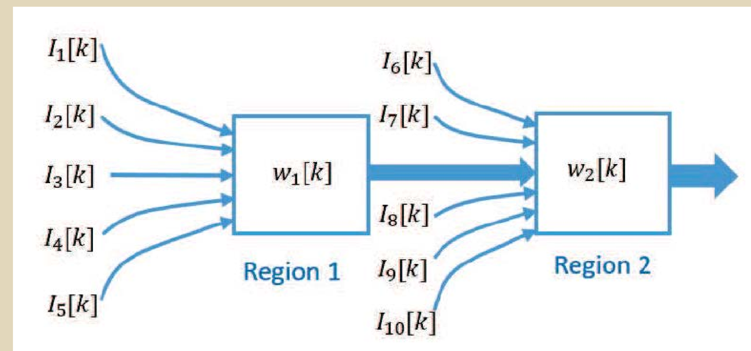
a)



b)

A simple example of first order dynamics and stationary control. a) 5 samples are sufficient to find the true minimum mean cost. b) Monte Carlo leads to heavy computational cost.



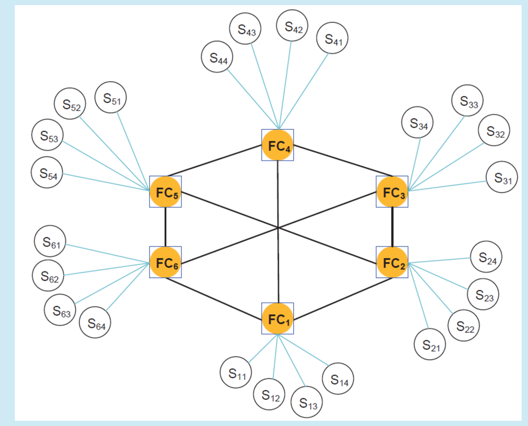


c)

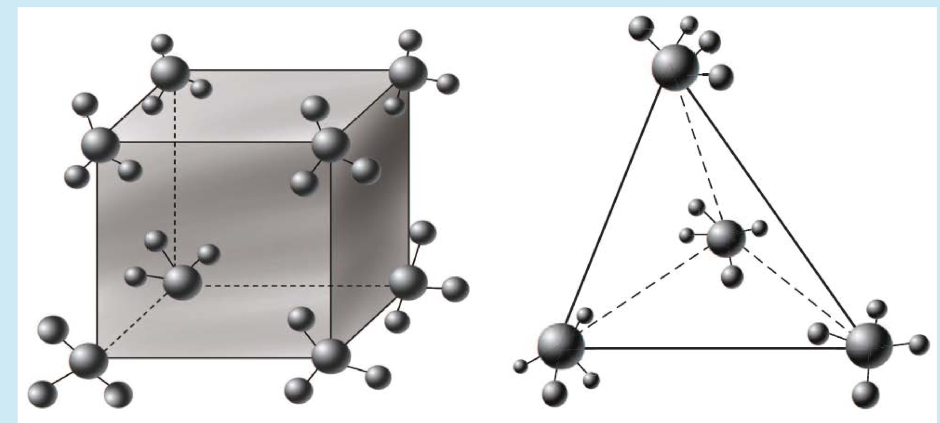
A example of 12 uncertainty parameter and time-varying parameters as well as control a) and b) control solutions, c) system structure.

Practical Networking to Facilitate Fast Decentralized Mobility Control

We developed a graph topology approach to study the layered structures for decentralized consensus (a typical decentralized control task). The results suggest that properly designed MLMG networks maintain decentralized communication while having the advantage of centralized structures with a significantly reduced number of transmissions.



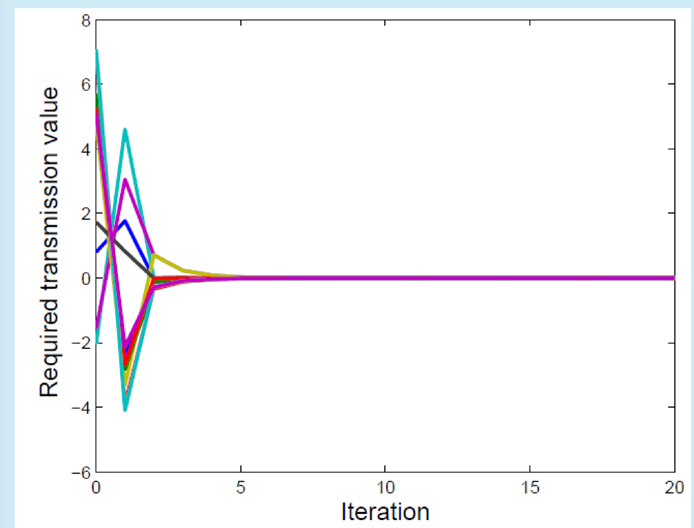
a)



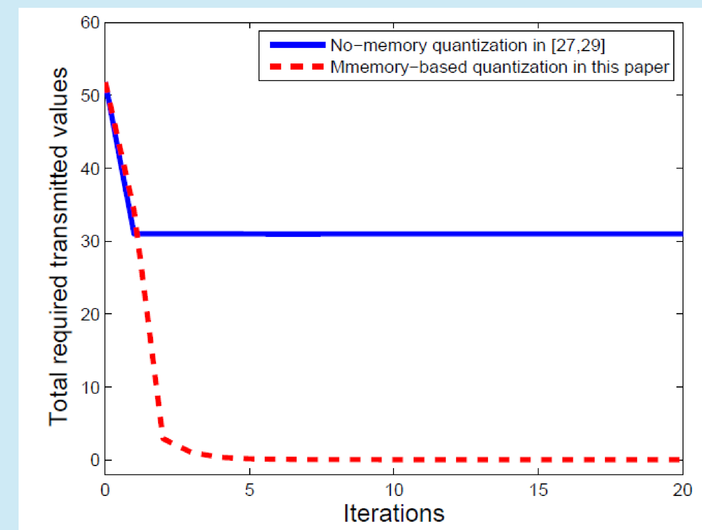
b)

Each group has one virtual fusion center and k sensors nodes. Each group has one and only one that node that communicates with m# virtual fusion centers. The consensus time is $\log_{\frac{k-1}{k+m_\#-1}}\delta$

We also developed analytical results for the use of memory to further reduce the volume of transmitted data



a)



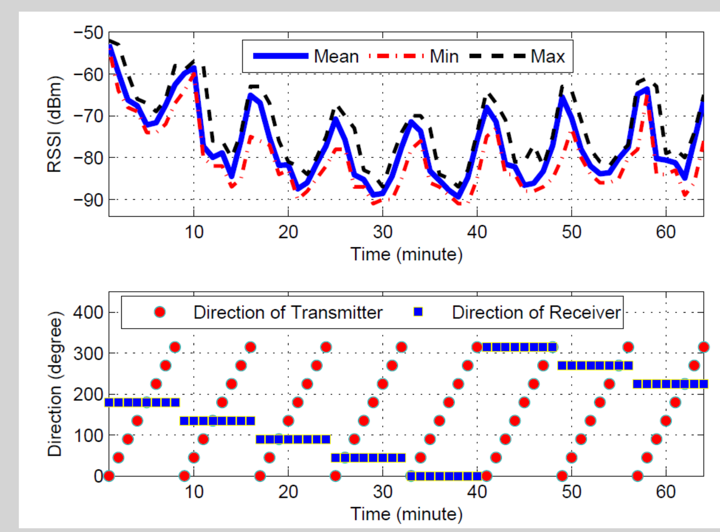
b)

a) Quantized consensus with memory over layered structures; b) comparison of quantized consensus with/without memory in terms of the volume of data per iteration

Testbed Development

We developed a testbed to implement and test UAV networking. a) prototype system b) tested signal strength

a)



b)

Some Key References

1. J. Yan, Y. Wan, S. Fu, J. Xie, and S. Li, RSSI-based decentralized control for robust long-distance aerial networks using directional antennas, submitted to IET Control Theory and Applications, 2016.
2. J. Xie, Y. Wan, K. Mills, J. J. Filliben, and Y. Lei, "Effective and Scalable Uncertainty Evaluation for Large-Scale Complex System Applications," submitted to SIAM/ASA Journal on Uncertainty Quantification, 2016.
3. J. Xie, Y. Wan, K. Mills, and J. J. Filliben, "Scalable Stochastic Optimal Control for Systems of High-dimensional Uncertainties," submitted to American Control Conference, 2016.