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WHERE DISCOVERIES BEGIN

CPS: Synergy: Collaborative Research: Design and Control of High-performance Provably-safe Autonomy-enabled Dynamic Transportation Networks

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Research Opportunity

Autonomy-enabled transportation networks are rapidly becoming a prominent Cyber-Physical-Systems (CPS) application area with tremendous potential for societal impact, as the autonomous systems technology penetrates into aerial/road vehicles and as the concept of connected vehicles emerge. The potential opportunities are not gone unnoticed. For example, unmanned aerial vehicle (UAV) based delivery networks has already attracted innovative companies like Amazon, Google, and Matternet (e.g. Fig. 1). Autonomous vehicles and vehicle sharing technologies may offer efficient and safe transportation infrastructure in the future. However, a deep understanding of the fundamental limits of and practical algorithm for autonomy-enabled transportation networks is essential for the large-scale deployment of these networks.

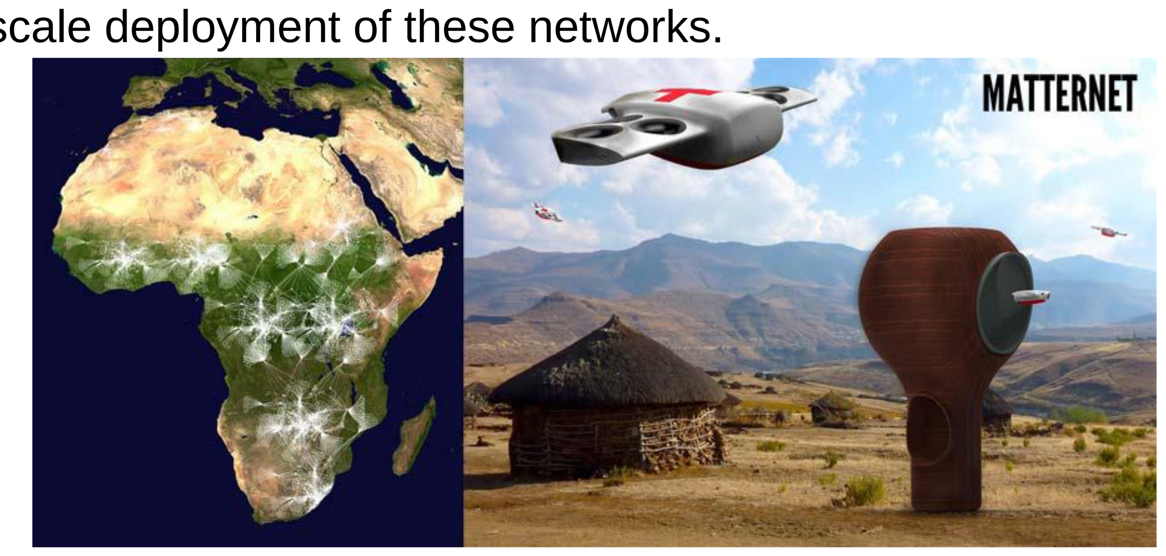

Fig. 1. Matternet envisions a team of small UAVs that can form a network to deliver much needed medicine in Africa. UAV network (left) and Matternet UAVs (right) are shown.

Research Objectives

This project has two research objectives. First is concerned with the design and control of individual hubs and links. Second considers the network as a whole.

The first research objective is to develop a foundational understanding of how automated vehicles can interact in hubs to maximize their performance, while guaranteeing safety at all times. This research objective addresses scientific questions such as: How does the performance of an individual hub scale with varying system parameters? What is the fundamental limit on performance metrics for a given system? How does the presence of human-operated vehicles among autonomous ones impact the system performance?

The second research objective is to develop rigorous bounds on performance with respect to the network variables including the number and the kinds of hubs and links, their connection structure, their dynamic nature, etc. This research objective addresses scientific questions such as: How does the performance of the whole network scales with varying network structure? Under what conditions a certain level of resilience or robustness is guaranteed? How can we quantify the systemic risk of local failures in the system? What are the optimal network coordination algorithms that guarantee high performance and safety?

Research Progress 1: Developed decentralized hub control laws with provable guarantees on performance and safety

We study decentralized control of intersecting vehicle flows (Fig. 2). For the case of two intersecting flows, a collaborative decentralized conflict resolution rule is proposed and analyzed for two intersecting flows. A Lyapunov function is defined to study the convergence of the conflict resolution dynamics under the proposed rule. It is shown that the aircraft flow safety and the conflict resolution dynamics convergence are guaranteed under the proposed decentralized conflict resolution rule. Simulations are provided to verify the analytically derived results (Fig. 3).

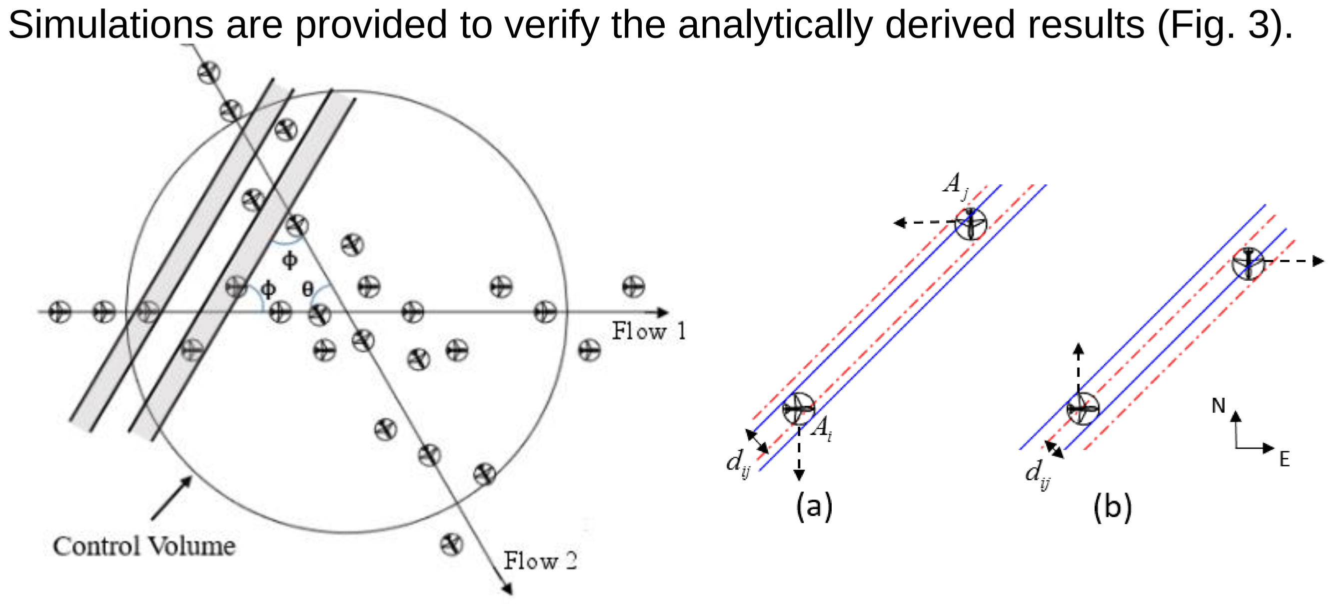

Fig. 2. (Left) Aircraft fly on two flows, moving in and out of a control volume. Shaded area define a "corridor" in which a conflict may occur. (Right) Two aircraft in conflict with (a) left touch and (b) right touch.

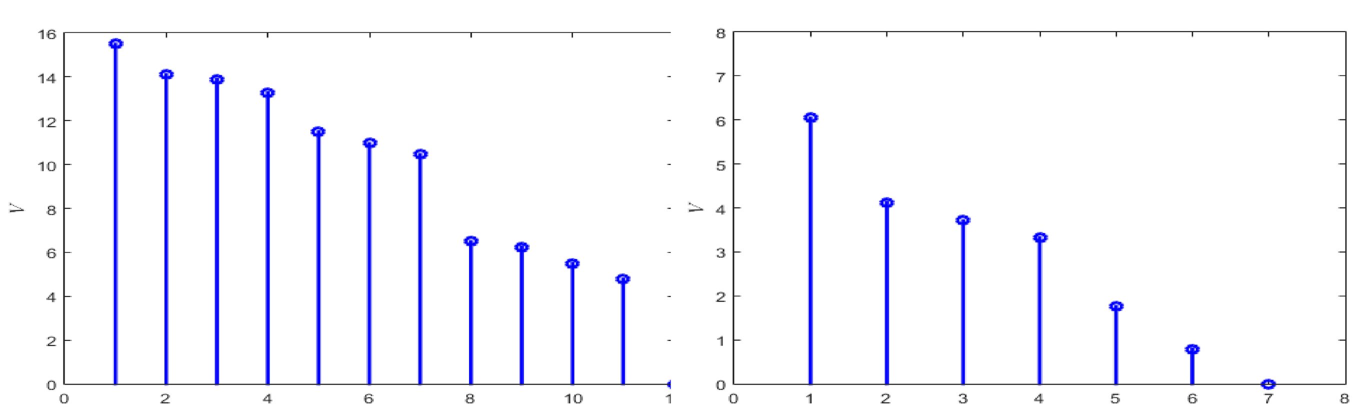

Fig. 3. Changes of the Lyapunov function V over time t for two intersecting aircraft flows at the intersection angle 90° (Left) and 60° (Right). V converging to 0 indicates that the decentralized control law successfully resolves the conflicts.

Research Progress 2: Developed link control laws and analyzed trade-off between efficiency and sustainability

Rapid advances in autonomous-vehicle technology may soon allow vehicles to platoon on highways, leading to substantial fuel savings through reduced aerodynamic drag. While these aerodynamic effects have been widely studied, the systems aspects of platooning have received little attention. We consider a class of problems, applicable to vehicle platooning and passenger ride-sharing, from the systems perspective. We consider a system in which vehicles arrive at a station according to a stochastic process. Our analysis explores the tradeoff between energy consumption and transportation delays. We derive the Pareto-optimal boundary and characterize optimal polices.

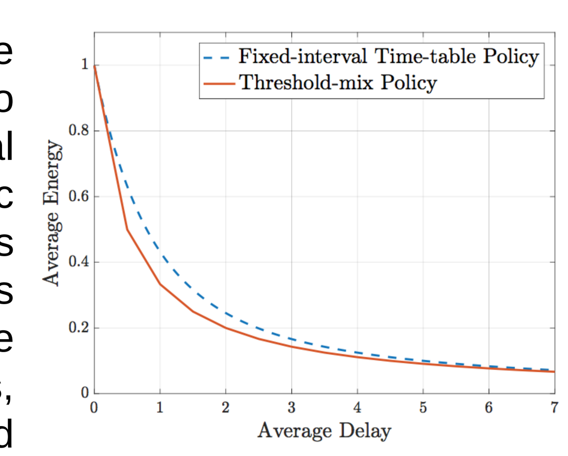

Fig. 4. The energy-delay tradeoff curve for both open-loop (timetable) policies and closed-loop (feedback) policies are shown. The Pareto-optimal boundary is derived analytically.

Research Progress 3: Modeled the human behavior in sensorimotor interaction with machines

We develop a human-machine physical symbiosis framework that helps understand human strategies in the control of machine under the stress of conflict avoidance (Fig. 5). The human and machine are modeled as two adaptive controllers in parallel with the plant (system under control). We have two feedback controllers working together, constantly adapting to each other's behavior and optimally stabilizing the plant to achieve a common goal. We also propose an inverse optimal control method to estimate human control strategy.

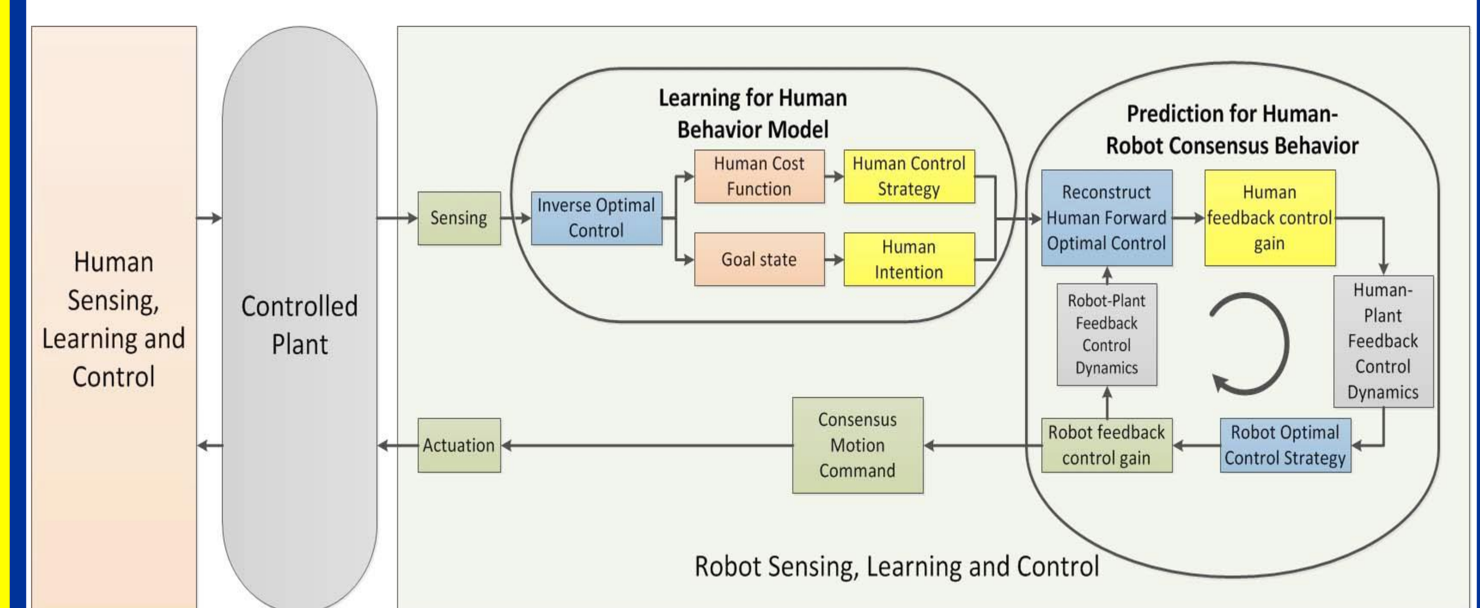

Fig. 5. Human-machine mutual learning, prediction of consensus movement, and optimal coordination process.

Future Work

Stability analysis for a decentralized control framework for intersecting flows of mobile agents. The control law that we proposed has a discontinuous right-hand side, and we will investigate the convergence properties of the Lyapunov function for the proposed decentralized control scheme.

References

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