Experimental Implementation of Open Multi-Agent Systems with Crazyflie UAVs

Keywords. Open Multi-Agent Systems, Multi-Robot Systems, Aerial Vehicles.

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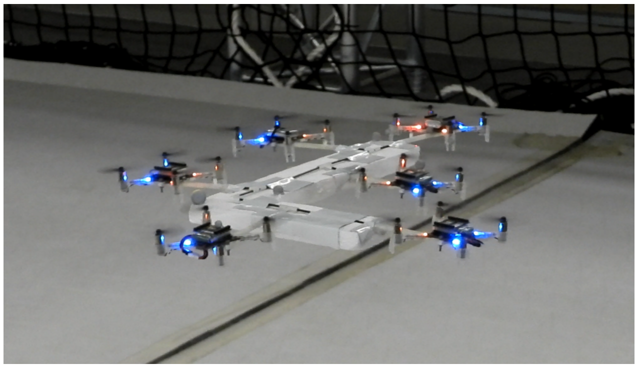
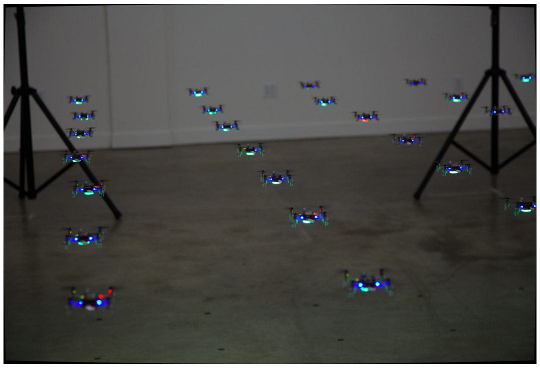
Context & Motivation: Multi-agent systems are increasingly applied to tasks such as exploration, transportation, and surveillance. While most experimental platforms assume fixed teams, many real-world scenarios require open systems, where agents can join or leave dynamically. The Crazyflie nano-quadrotor platform offers a safe, flexible, and scalable testbed to study such settings. This thesis will implement and validate open multi-agent coordination strategies on Crazyflies, bridging the gap between theory and practice.



(a) Multiple crazyflies performing a cooperative transportation task (source: `https://www.bitcraze.io/2023/11/adaptive-cooperative-flight-for-transportation-using-crazyflies/`).



(b) A team of crazyflies performing formation control (source: `https://rasc.usc.edu/robots/flying/crazyflie-g3/`).

Background: Open multi-agent systems (OMAS) are networks where agents and edges can dynamically be added to or removed from the system. They naturally arise in applications such as social networks, where the graph size changes with participant arrivals and departures [1], and in sensor-based robotic systems, where topology adapts based on inter-agent distances [2].

In this project, we experimentally validate the theoretical results on formation control of UAVs in an open-system setting. We use the tools of graph theory and switched systems to model the MAS and, Lyapunov theory for the stability analysis.

Problem description: We consider an OMAS composed of UAVs interacting over a dynamic topology described by an *(un)directed* graph. The control goal is for the

UAVs to achieve consensus-based formation. Specifically, three research directions are proposed:

- **Formation control in open settings:** We address the problem where UAVs dynamically join when additional UAVs are needed to support the mission or leave the formation due to limited energy. We model the OMAS using a switched system representation [3, 4, 2].
- **Constrained formation with connectivity maintenance and all-to-all collision avoidance:** We extend the previous result to a more realistic scenario, where UAVs communicate only within a limited sensing zone. We also include safety constraints, where a minimal inter-agent distance is defined to avoid all collisions between agents [2].
- (Optional) Extension to signed networks: In robotic networks, changes in dynamic topology due to environmental factors or mission updates can alter communication links, causing robots that initially collaborate to later compete for resources. [5, 4].
- (Optional) Extension to second-order dynamics.

Thesis objectives:

- Extension of current state-of-the-art algorithms for open multi-agent systems.
- Validate the proposed algorithms both in simulation and experimentally, using a formation of Crazyflie UAVs.

Expected workload: The work will include:

1. Familiarization with the Crazyflies and their APIs, as well as with ROS 2 and the rest of the experimental setup.
2. Literature review on graph theory [6, 7], switching systems [3], and barrier-Lyapunov functions [6, 8, 9].
3. Development of the algorithm in a simple simulation setting.
4. Experimental validation using multiple Crazyflies.
5. (Optional) Extension of the experiments for competitive networks.
6. If the work progresses sufficiently, writing of a scientific article to submit to a leading robotics or control conference or journal.

Prerequisites:

- Currently enrolled in a Master's program in electrical/control/robotics engineering or computer science

- Interest in working on both rigorous mathematics and hardware experiments.
- (optional yet desirable) Experience with ROS2 and mobile robots, strong background in control theory and robotics.

Research Questions:

- Recent advances have introduced controllers that enable agents to dynamically join and leave a multi-agent team while maintaining connectivity and avoiding collisions. However, these methods have so far been evaluated only in highly simplified simulation settings and typically assume unbounded control inputs.
  - Can such algorithms be transferred to real-world scenarios, where multiple agents must cooperatively achieve a task while operating under realistic input constraints?
  - Theoretical developments often rely on reduced-order dynamics that simplify robot behavior. Is this simplification still valid in real experiments—particularly at low speeds—or do higher-order effects need to be incorporated to guarantee stability and performance?
- When agents leave the network, they may act as articulation points whose removal disconnects the communication graph. Can we design strategies to anticipate and prevent such events, or decentralized reconfiguration policies that allow the remaining agents to restore connectivity autonomously?
- The open multi-agent systems control algorithms require a minimum average dwell-time between switches in the network topology (i.e. robots joining or leaving). How does the average dwell-time condition influence the practical applicability of the proposed control strategy? How can the parameters defining the average dwell-time condition be optimized?
- (Optional) How can the proposed model and control framework be extended to aerial robots such as Crazyflies operating under directed interaction topologies, which better capture unidirectional sensing constraints (e.g., limited field of view or anisotropic communication)?
- (Optional) How can the control framework be extended to signed interaction networks, where both cooperative and antagonistic behaviors coexist, for instance in the presence of adversarial agents?

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