Research Statement

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I specialize in **developing provably correct control strategies tailored for real-time implementation**, with a focus on multi-agent robotic systems. Drawing inspiration from disciplines such as control theory [1, 2, 3], collective intelligence, formal methods [4], sensor networks [5], and optimization [6, 7], I strive to provide innovative solutions to complex problems. To ensure the practicality of my work, I validate my controllers and motion planning algorithms through extensive simulations, typically conducted in ROS/C++ and Matlab followed by subsequent real-world experiments on physical platforms such as the mobile manipulator Stretch Robot, UAV Crazyflie 2.1, and mobile robot iRobot Create, customized to the specific task requirements.

A central question guiding my current research is: Can robots achieve complex tasks, with basic sensors and decentralized decision-making, rather than relying on a handful of expensive robots with advanced sensors? My research centers on optimizing efficiency and scalability within the constraints of limited onboard hardware resources. One of the challenges is enabling collaboration among cost-effective agents with minimal data exchange. The goal is to deploy large-scale robotic teams across diverse applications, including surveillance, environmental monitoring, security, search and rescue, crop monitoring, wildlife tracking, and fire control [8].

My approach involves the integration of certifiably safe motion planners with resource-efficient hardware for multi-agent systems [4, 5]. This raises intriguing research questions: What quantifiable trade-offs exist when considering hardware capabilities and algorithm complexity? Can we create a framework for exploring the design space and accommodating various hardware capabilities? Can collective intelligence algorithms adapt to individual agents' hardware limitations and capabilities, adjusting an agent's behavior based on task requirements, computing power, or sensory capabilities? This research direction reshapes our approach to multi-agent robotic systems by harnessing the full potential of numerous hardware capabilities across the robot team.

My current work at the Verifiable Robotics Research Group at Cornell is a concrete illustration of developing controllers taking into consideration the constraints imposed by hardware. Focusing on guarantees and minimal onboard capabilities, I am tackling the challenge of multi-agent robotic search and pursuit evasion in dynamic, unknown environments. By leveraging Lyapunov stability theory and problem-specific geometric constraints, I develop correct-by-construction controllers [4, 5] that rely solely on a robot's simple noisy sensors to construct an *impression* of its surroundings. This approach reduces the reliance on accurate localization, memory usage, or communication hardware. Notably, my work has produced several bounds on task and system design parameters. These include **quantifying trade-offs** such as the relationship between the number of sensors on a robot and the number of robots required to capture a target. I also provide theoretical guarantees for encapsulating faster evaders where each agent lacks knowledge of the evader's motion, **challenging a strong assumption** typically required in pursuit-evasion literature [9, 10, 11].

Building upon this work, my subsequent objective is to enhance the capabilities of systems such as Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs) to **solve the problem of coordination and navigation in unknown unstructured environments with limited communication** [12, 13]. The primary difficulty is adhering to operational constraints and avoiding collisions despite imperfect dynamic models and measurement noise. For instance, in underwater environments [14, 15] communication bandwidth is limited, inhibiting reliable cooperation among AUVs. Similarly, UAVs [16] used in search and rescue missions or for mapping wildfires often face challenges like GPS-denied areas, interference from collapsed metal-rich structures, malfunctioning equipment, and wireless bandwidth congestion by multiple decentralized response efforts [17].

Therefore, ensuring the reliable operation of both AUVs and UAVs mandates real-time execution of navigation, planning, and control algorithms, all while operating within the constraints of limited battery power. This multifaceted challenge underscores the significance of my ongoing efforts to develop guarantee-focused coordination and navigation methodologies for robotic teams.

Explicit communication-based strategies, though effective, encounter scalability issues and become less reliable in densely populated workspaces, straining onboard resources and compromising overall efficiency and safety. The gap between simulating and deploying robot teams in unstructured environments without explicit communication remains a significant challenge [12]. **A general solution that works independently of environmental conditions and team size** is crucial.

Considering this, distributed control and planning strategies using onboard computational resources offer the best safety and robustness. A recent study [18] introduces a theory for safe and efficient distributed constrained control for a swarm of UAVs, contingent on knowledge of nearby obstacles within the UAV's limited sensing range. In contrast, an alternative approach inspired by biological systems involves real-time obstacle reactions instead of using pre-existing obstacle information. Drawing inspiration from birds' obstacle avoidance abilities, researchers in [19] deploy UAVs in unstructured environments using onboard stereo cameras. However, this approach requires each UAV to broadcast trajectories to its neighbors. In response to these challenges, **my research will focus on developing online control algorithms that ensure task completion and provide safety guarantees for multi-robot systems while using minimal available information and limited onboard resources**.

Taking a step in this direction, I collaborated with researchers at the MERL's Control for Autonomy group to develop practical solutions for certifiably safe UAV operations with limited memory and computational resources. Our approach introduces refined versions of artificial potential functions [6] and robust invariant set-based motion planners [7] to achieve real-time execution on a Crazyflie equipped with limited memory, power, and noisy sensors in an environment cluttered with polyhedral obstacles. Notably, a recent study [20, 21] proposes a real-time decentralized trajectory planner based on linear spatial separations for a team of UAVs without using any communication while offering safety guarantees for static environments and noiseless sensors.

The next step is an extension to unknown environments like dense forests [19] by developing a provable multi-robot motion planner that accounts for dynamic obstacles and environmental changes while using limited data from low-resolution noisy sensors. To address this, I propose to build on my work [3, 1], where we developed a distributed adaptive control law based on Lyapunov methods for consensus in a networked system, despite agents measuring relative positions over a time-varying, undirected graph with unknown sensor bias. To reduce reliance on explicit communication, I will explore the **fusion of data from distance-detecting sensors such as LiDAR and visual-inertial odometry with drift avoidance navigational layers**. This approach necessitates using computationally inexpensive computer vision algorithms that require minimal memory, making collaboration with a computer vision research group essential.

Leveraging all available information and indirect interactions in the environment is essential when working with robots with limited onboard resources. For instance, the aerodynamic interference of rotor wakes between adjacent UAVs can impact stability [22]. I propose to model quadrotor downwash and **develop downwash-aware control strategies** [23] that leverage different optimal configurations to improve flight efficiency. Formally modeling and analyzing the downwash effect would translate to flexible constraints on the distances between UAVs. This, in turn, leads to improved utilization of onboard sensors such as distance-measuring sensors and the Inertial Measurement Unit (IMU) for better detection of neighboring UAV positions based on the downwash model. The UAV's self-adjusting capability resulting from this approach can enhance coordination even in the absence of direct communication. Additionally, I will build upon my prior research [5, 4] on navigation using minimal information from a robot's dynamic surroundings.

Overall, my goal is to advance practical and theoretically grounded solutions to enhance the safety and task completion of robotic systems in unstructured and dynamic unknown environments. By addressing the challenges of scalability, and adaptability in real-world applications, I aim to contribute to cost-effective and efficient control solutions across various domains.

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