

Toward Reliable and Intelligent Aerial Manipulation

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Research Vision: From Stable Contact to Autonomous Physical Intelligence

Aerial robots have the potential to transform how physical work is performed in places that are dangerous or inaccessible to humans—from wind turbines and transmission towers to nuclear facilities and disaster zones. Yet reaching these environments is not the same as working in them. An aerial robot must make and break contact, regulate interaction forces, respect stringent actuation limits, and respond to abrupt changes in dynamics—all while remaining airborne. Practical deployment also requires reasoning about finite battery capacity and, in some environments, operating without reliable GNSS positioning. These challenges expose a central gap between agile flight and truly autonomous aerial manipulation.

My long-term vision is to enable intelligent aerial manipulators to perform hazardous physical tasks autonomously, reliably, and at a level of operational effectiveness comparable to or exceeding human workers. The fundamental question driving my research is: *How can an aerial robot decide what to do, where and when to act, and how to execute physical interaction while maintaining rigorous guarantees of stability and safety?* I approach this question by connecting hybrid dynamics, safety-critical control, motion/force regulation, cooperative manipulation, and learning-based decision-making.

My research strategy is to build autonomy from a trustworthy physical foundation. Rather than treating high-level intelligence and low-level control as separate goals, I seek to make them mutually enabling: controllers establish the conditions under which physical interaction remains reliable; planning and coordination extend those capabilities to more complex tasks; and learning from simulation and human demonstrations expands the range of decisions an aerial manipulator can make. Within the broader interplay of perception, action, and aerial hardware, my primary contribution is the action module—decision-making, planning, and control—supported by theoretical analysis and hardware validation.

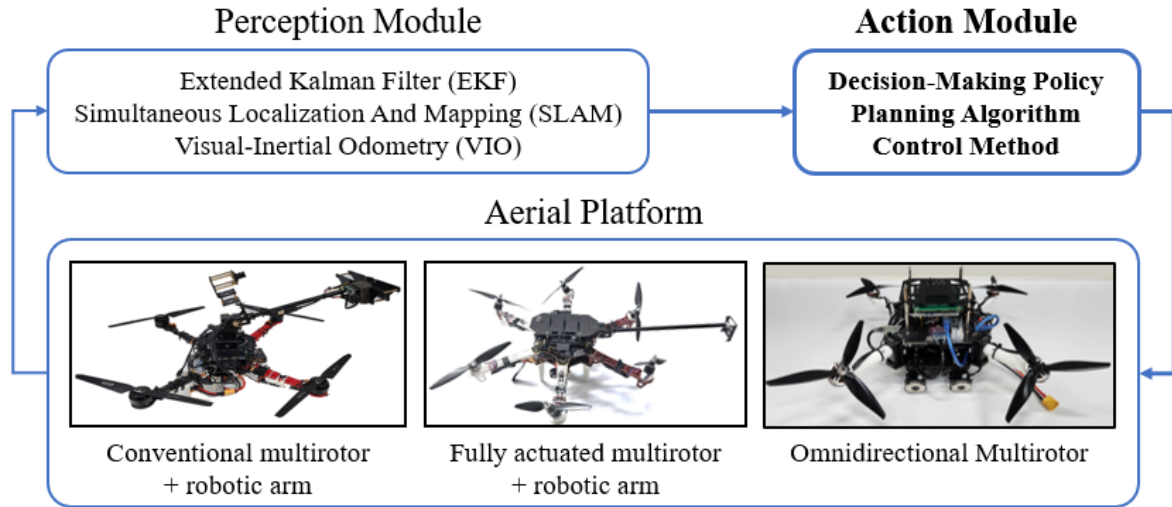


Figure 1: Structure of intelligent aerial manipulation (figure preserved from the original research statement).

Research Foundations: Making Aerial Physical Interaction Reliable

My previous work addresses three complementary failure modes in aerial manipulation: abrupt changes in contact dynamics, safety constraints during interaction, and the difficulty of regulating motion and force simultaneously. Together, these contributions form a foundation for reliable action beyond free-flight control.

Hybrid dynamics: remaining stable through abrupt transitions

Physical tasks such as extracting a wedged object can produce sudden changes in external forces. In [1], I developed a hybrid controller for such extraction tasks, focusing on improving the transient response immediately after release. I analytically established the stability and performance properties of the controller and validated them in hardware experiments. This work established an important principle for my research: successful aerial manipulation requires explicit treatment of discrete interaction events, not only continuous flight dynamics.

Safety-critical control: acting within physical limits

Aerial manipulators must remain safe even as they interact with uncertain surroundings and operate under limited motor thrust. In [2, 3], I developed safety-critical control approaches that account for thrust constraints, disturbance attenuation, and provable collision avoidance. I evaluated these approaches through pushing and pulling interactions with static and dynamic structures and object picking in cluttered environments. These results advance my broader goal of making safety a property of the control design rather than an assumption about the environment.

Motion/force control: maintaining reliable contact

Contact-rich tasks require a robot to control both its motion and the forces it applies. Building on my work in aerial motion/force control [4, 5], I designed a switched motion/force controller that explicitly considers static friction, maintains bounded contact-force errors, and avoids actuator saturation by adjusting motion and force profiles. This line of work was supported by the BK21 Ph.D. Fellowship and received an Honorable Mention in the Aerospace Paper Award from Korean Aerospace Industries. Collectively, my prior research shows how theoretically grounded control can support aerial manipulation across transitions, constrained motion, and sustained contact.

Future Agenda: Scaling Reliability into Autonomy

The next step is not simply to design another controller for another task. It is to turn reliable physical interaction into a reusable capability that supports diverse tasks, multiple cooperating robots, and increasingly autonomous decisions. I will pursue three interconnected directions.

Direction 1 — Generalizable, provably reliable interaction control

I am developing a versatile hybrid control framework that brings together the guarantees studied in my previous work: flight stability under discontinuous disturbances, adherence to motor-thrust limits, and compliant robot–environment interaction. The ambition is to move from controllers tailored to individual contact scenarios toward a common control foundation for a wider range of aerial manipulation tasks. Beyond instantaneous stability and actuator limits, I also intend to investigate battery-aware control and planning: how can a robot decide whether an interaction can be initiated, sustained, and completed safely with its available energy? This is a proposed extension of my current control research, not an existing result. The broader challenge is to preserve reliable physical interaction while accounting for both immediate safety constraints and mission-level feasibility.

Direction 2 — Decentralized cooperative aerial manipulation

Many physical tasks can benefit from several aerial manipulators acting together, but coordination introduces challenges that do not arise with a single robot. Building on my single-agent control and stability results, I aim to develop decentralized planning and control methods for cooperative manipulation. My focus is on minimizing internal interaction forces among agents, resolving adverse interactions between individually safety-critical controllers, and coordinating heterogeneous aerial manipulators. This direction asks how guarantees established at the individual-robot level can be extended to meaningful, reliable collective behavior.

Direction 3 — Learning skilled decisions from physics and human expertise

Reliable execution alone does not determine which task to attempt or when to attempt it. To support higher-level decision-making, I am developing a data-acquisition and learning pipeline with three connected components. First, I am building high-fidelity aerial-interaction simulators using physics engines such as Isaac Sim to reproduce contact-rich dynamics. Second, extending my haptic shared-control and bilateral teleoperation work [6], I am developing a visual–haptic teleoperation framework to collect demonstrations from skilled human operators. Third, I aim to organize aerial manipulation into task families and apply multi-task reinforcement learning to develop policies that can select and execute appropriate behaviors.

The longer-term objective is an aerial manipulation policy that uses visual information to assess the situation, reasons about the physical task, and selects an appropriate action. A further direction I intend to pursue is manipulation in GNSS-denied environments, where localization uncertainty can directly affect contact stability and task execution. Rather than treating navigation and manipulation as independent problems, I aim to explore how perception uncertainty can inform interaction-aware planning and safety-critical control. Simulation and human demonstrations provide complementary sources of experience; reliable control provides the foundation for executing those decisions in the physical world. Together, these components chart a path toward expert-like aerial manipulation without assuming that learning alone can resolve safety-critical physical interaction.

Long-Term Impact

I envision aerial manipulators progressing from remotely supervised tools to autonomous physical workers capable of operating in hazardous environments, including locations with limited onboard energy and unreliable GNSS. My research program connects guaranteed interaction control, decentralized coordination, and learned task-level decision-making under one objective: making intelligent aerial physical interaction both capable and dependable. By building higher-level autonomy on a rigorously validated control foundation, while expanding toward energy-aware and localization-uncertainty-aware operation, I aim to help close the gap between aerial robots that can reach difficult places and aerial robots that can reliably perform useful work there.

References

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