Research Statement

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1. Vision: Fully Autonomous Aerial Manipulation

Aerial robots can perform dexterous tasks in diverse environments due to their exceptionally high maneuverability compared to human workers and ground robots. This capability enables them to perform robotic manipulation in hazardous locations—such as high-altitude or contaminated areas, including wind turbines, transmission towers, the interiors of nuclear power plants, and disaster zones. **Carrying out tasks involving physical interaction with aerial manipulators — that is, aerial robots equipped with robotic arms — can enhance economic efficiency and significantly reduce the risk of human damages.** In this context, my ultimate goal is the full replacement of human workers in dangerous environments with aerial manipulators. However, it is widely acknowledged within the aerial robotics community that **fully autonomous aerial manipulation (similar to Level 5 of autonomous driving system) has not yet been achieved**.

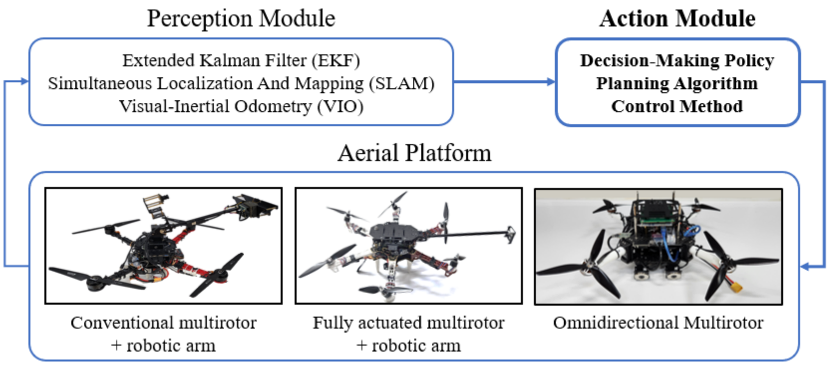

Fig. 1 Structure of fully autonomous aerial manipulation

As shown in Fig. 2, a fully autonomous aerial manipulation system typically consists of three components: an action module, a perception module, and an aerial platform. In the direction of fostering mutual and positive feedback among these three modules, my research primarily focuses on the development of the **action module**, which enables aerial robots to autonomously determine **what to do (decision-making policy)**, **where and when to go (planning algorithm)**, and **how to go (control method)**. All these elements are developed to guarantee the aerial manipulator's stability, safety, and operational efficiency comparable to — or even surpassing — that of human workers, **supported by theoretical proofs and experimental validations**. I believe that this modular approach provides rigorous theoretical guarantees for reliable aerial manipulation and enables a module-by-module debugging when issues arise.

My past works have focused on developing control methods for multirotor-based aerial manipulators that physically interact with their surrounding environments, while ensuring:
(i) flight stability under abrupt changes in dynamics [1],
(ii) avoidance of controllability-loss due to motor saturation [2], and
(iii) no contact-loss during contact-based aerial manipulation [3], [4] **(Conducted with**

support from the Brain Korea 21 (BK21) Ph.D. Fellowship and recognized with an Honorable Mention in the Aerospace Paper Award presented by Korean Aerospace Industries (KAI), Ltd.)

Currently, I am designing a versatile controller that integrates the above properties and can be applied to various types of aerial physical interaction, as a unification of my previous works on aerial manipulator controllers. **In parallel**, I am also developing a planning algorithm for generating dynamically feasible, collision-avoiding trajectories for an aerial manipulator.

For future works, my first goal is to design and control an omnidirectional multirotor equipped with a robotic manipulator for operation in GNSS-denied environments, using onboard sensors such as cameras or LiDAR. This will enable autonomous aerial manipulation in unstructured environments. **Second,** I plan to develop planning algorithms that avoid motor saturation and collision in cluttered environments, and enhance operational efficiency such as short task completion time and high energy-efficiency. **Third,** I aim to design a policy trained via learning from demonstrations provided by skilled human experts for a variety of manipulation tasks. To support this, I will construct a high-fidelity aerial manipulation simulator to reduce the sim-to-real gap and ensure zero-shot performance to downstream tasks. In addition, to obtain real-world training data, I will construct a framework for visual-haptic-based teleoperation of an aerial manipulator.

2. Past Works: Provably Stable Low-Level Controllers

Hybrid Control: In [1], I designed a hybrid controller for extracting a wedged object (e.g., plug-pulling), with a focus on enhancing transient performance after the extraction. The performance improvement and system stability were analytically derived and experimentally validated through both mathematical analysis and hardware experiments.

Motor Saturation-Aware Control: In [2], I designed a safety-critical controller that guarantees motor thrust limits and disturbance attenuation performance. This control scheme was validated through pushing and pulling experiments involving both static and dynamic structures.

Switched Motion/Force Control for Stable Contact: Based on my previous works on motion/force control of an aerial manipulator [3, 4], I designed a motion/force controller that explicitly models static friction and adjusts motion/force profiles to maintain bounded contact force errors and prevent actuator saturation.

3. Ongoing and Future Works: Summing Up Controller and Moving Towards High-Level Planners and Decision-Making Policies

Versatile hybrid controller with guaranteed stability, safety and reliability: Building upon my previous publications, I am designing a controller applicable to a wide range of aerial manipulation tasks, while simultaneously ensuring flight stability under discontinuous external disturbances, motor thrust limitations, system passivity, and compliant robot–environment interaction.

Planning algorithm in complex environments: Leveraging the advantages of superquadrics

— compact parametrization, wide shape variability, and smooth surface representations — I will propose a method for generating dynamically feasible, collision-free trajectories for a multirotor and the links of an attached robotic arm.

Frameworks for data acquisition and imitation learning-based decision-making policy:

1) **High-fidelity simulator of aerial physical interaction:** I aim to build simulators leveraging commercial physics engines that accurately replicate the dynamic behavior of aerial manipulators physically interacting with surrounding environments.

2) **Visual-haptic bilateral teleoperation framework**: Following my preliminary work on haptic-based shared control of an aerial manipulator extracting a wedged object [5], I plan to design a visual-haptic bilateral teleoperation framework for aerial manipulation to gather real-world data for imitation learning.

Leveraging data acquired from high-fidelity simulators and skilled human experts, I ultimately aim to obtain a decision-making policy for aerial manipulators. This policy includes situation awareness based on visual information (serving the role of human vision), reasoning behind the interpretation, and task selection accordingly.

References

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[3] J. Byun, J. Kim, D. Eom, D. Lee, C. Kim, and H. J. Kim, "Image-based time-varying contact force control of aerial manipulator using robust impedance filter," IEEE Robotics and Automation Letters, 2024.

[4] J. Byun, B. Kim, C. Kim, D. D. Oh, and H. J. Kim, "Stable contact guaranteeing motion/force control for an aerial manipulator on an arbitrarily tilted surface," in 2023 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2023, pp. 5345–5351.

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