Dexterous Aerial Manipulation in Complex Environments

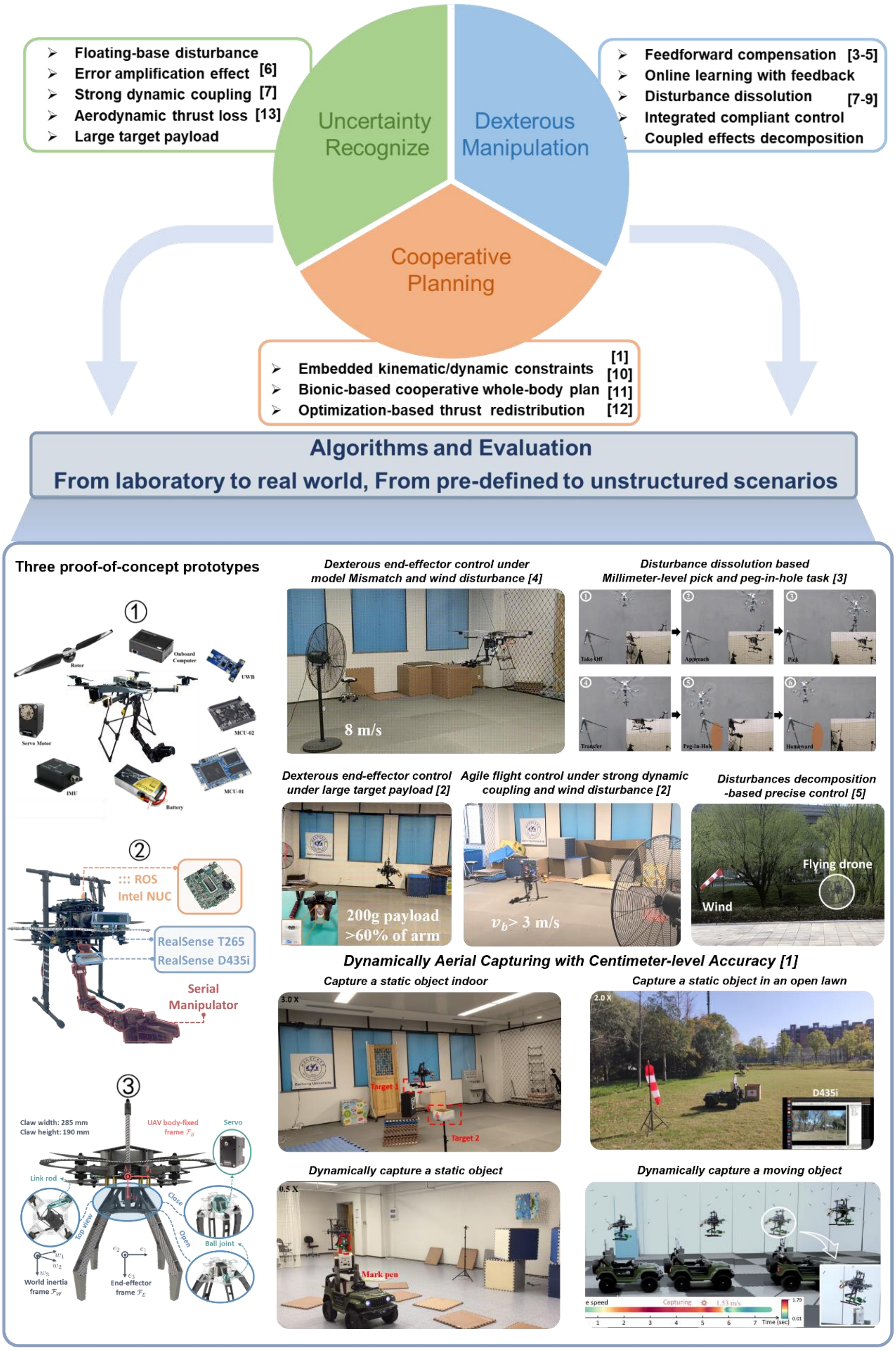

Fig. 1. An overview of my Ph.D. research

Background. Aerial robots have emerged as a pivotal component within the modern digital ecosystem, demonstrating remarkable agility and achieving milestones such as human-competitive drone racing and intelligent navigation through complex environments. Nonetheless, a significant capability gap persists: the majority of these systems remain limited to passive operations, unable to perform active physical interactions-such as repairing, assembling, or manipulating objects-as envisioned in the human's prospect of robots serving as workers, co-workers, and dynamic agents in logistics.

Ph.D. Research. Although the active feature allows aerial manipulators to perform diverse interaction tasks, their manipulation capability is severely constrained by various uncertainties. Therefore, the topic of my Ph.D. research focuses on dexterous manipulation control of aerial manipulator in composite disturbances (Fig. 1). Three key challenges are addressed: how to recognize different uncertainties, how to tackle uncertainties to achieve dexterous aerial manipulation, and how to cooperatively regulate system states to precisely capture different targets under multiple constraints. 1) For the first challenge, I followed the research route from separate processing to deep-coupling estimation[6][7][13]. By combining analytically modeling with data-driven learning, composite disturbances and system controllability were quantitatively depicted. 2) For the second challenge, beyond feedforward compensation, I developed several uncertainty rejection schemes to enable dexterous aerial manipulation in complex environments[3][4][5][7][8][9]. Notably, by integrating advanced learning techniques with model-based control, millimeter-level pick and peg-in-hole task[3] is achieved by aerial manipulator (the highest accuracy publicly reported to date). 3) Inspired by the morphology of birds preying, I proposed a bionic-based framework to cooperatively regulate system motion. Especially, the seamless integration from body, perception, planning to action endows aerial manipulator with dynamic and precise interaction capabilities, breaking from the paradigm in which aerial robots are restrained in pre-defined environments[1][10][11][12].

Further Work. The past decade has witnessed remarkable progress in artificial intelligence (AI), particularly with the rise of deep learning over multilayer neural networks such as CNNs, transformers, reinforcement learning (RL), and diffusion models. Within the AI for Robotics strategy, robots have made significant breakthroughs in motion control. However, current approaches remain far from reaching the dexterity of human. For instance, humans are capable of continuously regulating state and acquiring new power throughout entire lifespan to adapt to complex and dynamic external environments. Moreover, neural circuits inherently balance accuracy and robustness in the presence of composite uncertainties. To bridge this gap, plenty of algorithms including domain randomization/adaption, meta-learning, curriculum learning, and imperative learning are being explored to improve both accuracy and generalization.

Although the data-based methods have achieved impressive results, the unexplainable approach would be prone to failures that can neither be predicted beforehand and nor be fully explained afterwards, posing a serious threat to system safety. Compared to totally knowledge-agnostic approach to learning, the combination of control methods with provable guarantees is a more sensible way forward. My next purpose is to establish a cooperative and hierarchical framework by incorporating prior knowledge and leaning approaches. After embedding the framework, robots can gracefully perform different delicate manipulation. Moreover, the skills learned by individual robots can be applied to different robots and environments without sacrificing original capability.

Refs.

[1] **M. Wang**, J. Jia, S. Zhou, K. Guo, X. Yu, and L. Guo, “Dynamically aerial capturing with centimeter-level accuracy,” ***Science Advances****, under review, 2025.*25.

[2] **M. Wang**, J. Jia, K. Guo, X. Yu, and L. Guo, “A learning-enhanced control scheme for aerial manipulator under composite disturbances,” ***Fundamental Research****, under review, 2025.*25.

[3] **M. Wang**, Z. Chen, K. Guo, et al., “Millimeter-level pick and peg-in-hole task achieved by aerial manipulator,” ***IEEE Transactions on Robotics***, vol. 40, pp. 1242–1260, 2024.

[4] **M. Wang***, S. Lyu*, Q. Liu, Z. Yang, K. Guo, and X. Yu, “Precise end-effector control for an aerial manipulator under composite disturbances: Theory and experiments,” ***IEEE Transactions on Automation Science and Engineering***, vol. 22, pp. 4006–4021, 2025.

[5] J. Jia*, **M. Wang***, Z. Yang, et al., “Learning-based observer for coupled disturbance,” in ***ICRA2026,*** *under review.*

[6] W. Zhang, Q. Liu, **M. Wang**, et al., “Design of an aerial manipulator system applied to capture missions,” in ***International Conference on Unmanned Aircraft Systems (ICUAS)***, 2021.

[7] X. Yu, **M. Wang***, et al.* An anti-disturbance control method of the end-effector of aerial manipulator. ZL202211166794.X

[8] X. Yu, **M. Wang***, et al.* A hierarchical control approach for aerial manipulator against composite disturbances. ZL202310138154.6

[9] X. Yu, **M. Wang***, et al.* An optimization-based thrust distribution method for coaxial multi-rotors considering the overlap effect. ZL202411104509.0.

[10] K. Guo, **M. Wang***, et al.* An anti-disturbance control method for aerial manipulator based on full-state coupled dynamics. ZL202411104478.9.

[11] K. Guo, **M. Wang***, et al.* An integrated cooperative planning method for aerial manipulator toward target capturing. ZL202411104450.5.

[12] K. Guo, **M. Wang***, et al.* An anti-disturbance control method for aerial manipulator based on full-state coupled dynamics. ZL202411104478.9.

[13] L. Guo, **M. Wang***, et al.* A pose control method for aerial manipulator against composite disturbances. ZL202110993793.1.