Fully and Semi-Autonomous Aerial Physical Interaction with Reliability and Versatility

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I. Motivation

Aerial manipulators, which integrate an unmanned aerial vehicle (UAV) with a robotic arm, are widely used for tasks involving physical interaction in environments hazardous to human operators or unsuitable for ground-based robots such as walls or windows of tall buildings, wind turbines, earthquake disaster areas, or damaged nuclear power plants. However, planning and control for aerial manipulators interacting with their surroundings remain challenging due to several inherent characteristics of aerial robots. These challenges include potential stability loss from external disturbances or actuation limits, performance degradation due to abrupt changes in dynamics and discontinuous contact friction, and the presence of unknown dynamics in the interacting object. To resolve such issues, the approaches below can be incorporated into a potential solution:

- **Hybrid System Modeling**: When an aerial manipulator performs a task involving physical interaction, its dynamic model inherently consists of two or more operative modes. Therefore, designing controllers based on hybrid dynamical system frameworks — such as hybrid automata, switched systems, or impulsive systems — can improve the performance of aerial physical interaction.
- **Flight Stability and Safety**: Planning and control modules for the reliable aerial physical interaction must guarantee flight stability with the consideration of external disturbances such as wind gusts, model uncertainties, switching behavior between multiple operative modes, and actuation limits.
- **Low-Complexity**: Since typical aerial robots are equipped with low-weight processors, their controllers have to be executed within a rapid rate ($>$ 100 Hz). Thus, it is preferred to design low-complexity control algorithms.
- **Fully and Semi-Autonomous Solution**: For a single specific task, an aerial manipulator can be autonomously operated solely depending on the vehicle's decision. Otherwise, for the tasks involving multiple subtasks and complex actions, partially relying on the human's decision-making ability, e.g., remote teleoperation, might be an alternative solution.

With the solutions above, I have proposed several planning and control methods for the reliable aerial physical interaction.

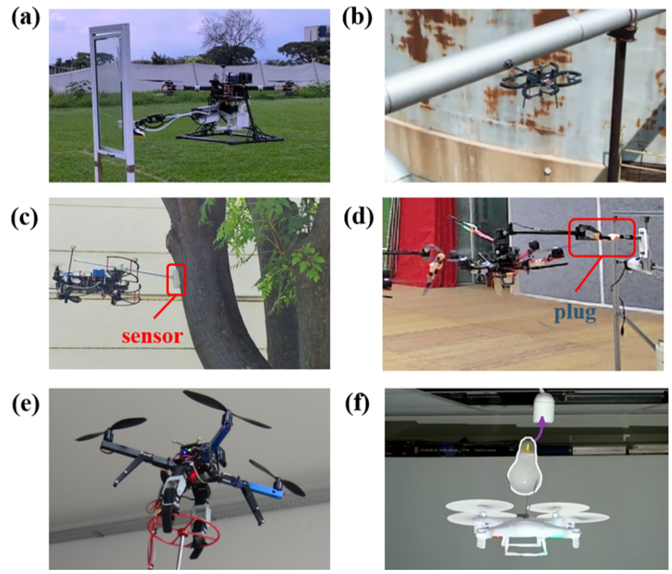

Fig. 1: Examples of APhI tasks including (a) window-cleaning [24], (b) Non-Destructive Testing (NDT) on industrial pipes [19], (d) sensor installation and retrieval [11], (e) plug-pulling [1], (e) valve turning [17], and (f) light bulb-replacing [16]

II. Past Works

A. Transient Performance Enhancing Hybrid Controller for APhI Tasks Involving Abrupt Changes in Dynamics [1]

Among the tasks involving aerial physical interaction, I have conducted research on the control of an aerial manipulator that undergoes abrupt changes in dynamics — for example, extracting a plug from a socket or the sudden disappearance of a contact surface during pushing and sliding on a surface. In this regard, I designed a hybrid controller by dividing the operation into two flight modes: free-flight (FF) and physically interacting (PI) modes. To enhance the transient performan ce after flight mode transitions, we formulate respective control strategies for each mode and an initialization strategy after each transition. I also theoretically prove that the magnitude of the initial overshoot in the state variables immediately after object extraction is bounded. For the controller design and stability analysis, I focus on handling external disturbances (e.g., wind, aerodynamic effects, and interaction wrenches) and uncertain model parameters (e.g., mass, moment of inertia, and gravitational acceleration) during each flight mode and their transitions. As an example of such a task, we conduct a plug-pulling experiment, and the results using the proposed controller are compared with those from two existing control methods.

B. Hybrid Motion/Force Control of Aerial Manipulator [2, 4]

Among APhI tasks, there exist several tasks involving switching behavior between two flight modes, such as contact-based manipulation involving push-and-slide on a surface. For these tasks, there still exists a remaining issue where the system might not be stabilized within a finite number of switches. This issue highlights the need to regulate the contact force between the end-effector and the surface. Hence, I design a stable contact guaranteeing reference trajectory generation method, with and without vision-based sensors. Using this method, the aerial manipulator can achieve stable contact within a finite number of switches by precisely tracking a given desired force profile, whether constant or time-varying. Moreover, the contact stability of the APhI system is theoretically proved by showing the precise force-tracking performance.

C. Safety-Critical Control of APhI [5]

For APhI with multirotor-based aerial manipulators, motor thrust limits become a crucial challenge in ensuring safe flight. Although the external wrench arising from physical interaction must be well attenuated for precise pose-tracking control, focusing solely on this attenuation may lead to motor saturation. To resolve this issue, we design a disturbance observer (DOB)-based safety-critical controller for various types of APhI in uncertain environments, without relying on direct measurement or estimation of the interaction wrench. To that end, I propose a safety filter that adaptively adjusts the desired pose and twist of the aerial manipulator to guarantee flight safety with respect to motor thrust limits for various types of APhI tasks. This filter incorporates a system model that integrates the aerial manipulator's dynamics with the DOB structure [10]. The superiority of the proposed controller over existing APhI control approaches is validated through pushing and pulling experiments involving both static and dynamic structures.

III. Ongoing and Future Work

A. Static Friction-Aware Control for Aerial Push-and-Slide

Numerous studies have addressed the control of aerial manipulation involving pushing and sliding motions, such as in nondestructive testing (NDT) [13, 21], aerial painting [18], and wall-cleaning tasks [20]. According to [2], precise regulation of the contact force is crucial for ensuring stable contact. Moreover, static friction at the end-effector can lead to motor saturation and loss of controllability, leading to the necessity to adaptively modify the desired motion accordingly. To enable reliable aerial push-and-slide interaction, this work presents a force-tracking controller that ensures convergence of the contact force error to an arbitrarily small bound, even under time-varying force profiles. Also, theoretical conditions are derived to guarantee stable contact within a finite number of switching events, and a gain selection strategy is proposed accordingly. To address potential destabilization due to motor saturation under large static friction, a motion/force trajectory generation method is also developed. The validity of the proposed controller is demonstrated through comparative experiments on aerial push-and-slide tasks.

B. Controller for Reliable, Safe and Versatile Aerial Physical Interaction

Building upon [5], I aim to design a controller applicable to a wide range of aerial physical interaction (APhI) tasks, while ensuring flight stability against discontinuous external disturbances, motor thrust limits, system passivity, and compliant robot–environment interaction. In addition, I will conduct a theoretical analysis to guarantee both flight stability and the recursive feasibility of the safety set, explicitly incorporating motor thrust constraints and passivity considerations. For hardware validation, both static and dynamic APhI tasks will be executed.

C. Planning and Control of Aerial Manipulator in Complex Environments with Superquadrics

According to [27], superquadrics (SQs) have three key advantages shown below:

- **Compact parameterization**: SQs can be represented using only 11 parameters — 5 for shape and 6 for pose — which significantly reduces both storage requirements and computational overhead.
- **Wide shape variability**: SQs can approximate a broad range of shapes, from near-spherical to box-like.
- **Smooth & differentiable surfaces**: Their continuously differentiable (C) boundaries make them suitable for gradient-based computations and optimization.

Building on these advantages, I will propose a method for generating dynamically feasible, collision-avoiding trajectories for aerial manipulators. The aim of this approach is to guarantee the recursive feasibility of the constraint set while improving success rate, computational efficiency, and trajectory smoothness.

D. Transient Performance-Enhancing Reinforcement Learning (RL) Policy for an Aerial Manipulator Against Abrupt Changes in Dynamics

Due to the inherent aspect of APhI, tasks in this domain often induce multiple dynamic modes and discontinuous jumps in the vehicle's state variables, such as pose and twist. Although my previous work, [1], dealt with improving transient performance after the abrupt change in dynamics, it primarily addressed the reduction of overshoot in an indirect manner — mitigating abrupt state transitions after object extraction from a broader perspective — rather than explicitly minimizing the maximum overshoot occurring shortly after the extraction. While numerous studies have approached overshoot reduction through cost-optimized controller design, they tend to neglect the impact of external disturbances, particularly in cases where those disturbances exhibit sudden increases or decreases.

Building on the aforementioned limitations, I aim to develop a reinforcement learning (RL)-based controller for APhI tasks, incorporating the following two key advantages:

- Detection of abrupt changes in dynamics or the vehicle's state using only onboard sensing, without relying on direct force feedback.
- Direct minimization of transient overshoot immediately following contact events or dynamic transitions.

To this end, I will refer to several recent studies that integrate reinforcement learning (RL) techniques with aerial robotic systems, including but not limited to [15, 26, 14, 6, 23, 25, 8, 7, 9, 28, 12].

E. Haptic-Based Bilateral Teleoperation of Aerial Physical Interaction

According to [3], there are certain situations in which fully autonomous control of an aerial manipulator outperforms human-supervised operation. These include moments such as when a plug is pulled out of a socket or when contact between the robot and the environment suddenly disappears. To address these cases, I am currently working on the design of a teleoperation framework for aerial physical interaction (APhI) based on the concept of shared autonomy introduced in [22].

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