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Control Strategies for Real-Time Aerial Manipulation with Multi-DOF Arms: A Survey

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Abstract— **This survey summarizes key control approaches and architectures that reflect the state-of-the-art in aerial manipulation. The central objective is to provide a thorough resource for researchers exploring multirotor configurations suitable for real-time aerial manipulation applications. The focus is on evaluating and comparing prototype systems and their corresponding controller designs, emphasizing real-time implementation, regardless of the number of DOFs of the attached manipulator(s) and of specific applications. The survey groups control methods in three categories based on the specific architecture that is followed: coupled, partially coupled, and decoupled. The metrics used for the comparative study include system configuration, total weight, modeling approach, control architecture, robustness, implementation complexity, task execution precision, and achieved results (via simulations or experiments).**

I. INTRODUCTION

Research on Unmanned Aerial Vehicles (UAVs) and Unmanned Aircraft Systems (UAS) has grown significantly over the past two decades, driven by applications like search and rescue [1], fire monitoring [2], and aerial delivery [3], to name but only three, where UAVs primarily observe or transport loads without complex interactions. However, tasks such as high-voltage transmission line inspection [4], assembly operations [5], and solar panel cleaning [6] require UAVs to actively interact with their environment. These tasks demand not only navigation, stability, and control but also highly accurate manipulation capabilities to ensure precision and effective interaction. The field of aerial manipulation [7] addresses this need, featuring multirotor UAVs equipped with robotic arms that operate autonomously, semi-autonomously, or through teleoperation, handling tasks that are dangerous, costly, or impractical for humans.

Overall, aerial manipulation introduces considerable challenges, such as maintaining flight stability when external forces and torques are generated by the attached robot arms or payloads. The integrated multirotor system is subject to complex and nonlinear dynamics due to underactuation and inherent weight and payload constraints [8]. The configuration itself must be feasible for real-time functionality. For example, robot manipulators often use conventional servo-based actuators, which may be insufficient or unsuitable to provide the torque control required for precise and stable manipulation for task completion [9]. Therefore, the underlying control strategies that are adopted play a pivotal role in addressing these challenges, particularly in ensuring stability, precision, and robustness during interaction tasks.

Multirotor control approaches include linear, linearized, and nonlinear designs [4]. Hierarchical architectures are commonly used for stability and trajectory tracking, separating angular and linear dynamics. For handling complex aerodynamics, approaches include backstepping, impedance control, and optical flow techniques. Robust designs, such as adaptive controllers and disturbance observers, address external disturbances and uncertainties, while passivity-based methods like Port-Hamiltonian approaches provide robustness and precision without requiring exact model compensation [4]. Aerial manipulation adds a level of complexity to these strategies, including managing the forces between the multirotor, arm, and environment while mitigating disturbances and accounting for system uncertainties. Developing controllers for agile flight with heavy payloads, precise manipulation, and accurate end-effector tracking demands considerable effort.

The study considers single multirotor UAVs equipped with rigid multi-DOF arms. The focal point of this paper is on classifying control strategies considering the dynamic coupling between the multirotor UAV and the integrated arm, as it strongly affects computational demands (for real-time feasibility and applicability) and the tasks to be executed. The research is the natural outgrowth of previously completed and published research by the authors on cooperative aerial manipulation [10][11][12], but the focus is now shifted on investigating the adopted controller design approaches. Therefore, the multirotor-arm(s) configuration and the underlying control architecture offers guidance on the preferred approach to be followed given a set of tasks to be executed. The evaluation is performed in terms of implementation complexity, precision, robustness, and adaptability to dynamic conditions, to identify the best possible controller designs for practical tasks.

The rest of the paper is organized as follows. Section II presents and classifies the adopted, derived, and used control strategies (controller design techniques) in three categories, coupled control, partially coupled, and decoupled aerial manipulation systems. Section III concludes the survey and provides future directions for research.

II. CLASSIFICATION OF CONTROL APPROACHES

In this section, derived control algorithms, techniques, and controller designs for aerial manipulation are reviewed and

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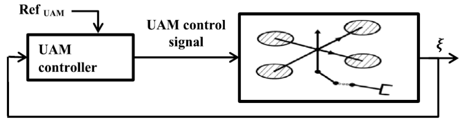

Fig. 1. Scheme of coupled UAM control [14] - Ref_{UAM} (desired states), ξ (state feedback)

analyzed based on the level of coupling between the multirotor UAV and the attached robot arm(s). System modeling uses either Euler-Lagrange (EL) formulation for symbolic matrix representation or recursive Newton-Euler (RNE) for coding simplicity [4].

A. Coupled Control Strategies

Coupled control approaches consider the multirotor UAV and the attached robot arm as one entity. Controller design considers full dynamics coupling, which is explicitly reflected in the inertia matrix [9], see (1)

$$M(r) = \begin{bmatrix} M_p & M_{pr}(r) \\ M_{pr}^T(r) & M_r(r) \end{bmatrix} \tag{1}$$

where $M_p = m_L I_3 \in \mathbb{R}^{3\times3}$ represents the total mass of the unmanned aerial manipulator (UAM) system, $M_{pr}(r)$ captures the coupling inertia terms between the quadrotor and the robot arm, and $M_r(r)$ corresponds to the inertia matrix of the robot arm links [13]. The coupling terms $M_{pr}(r)$ quantify interaction forces between the manipulator and UAV, growing significantly with arm extension—a challenge for decoupled control approaches.

The multirotor-manipulator system is controlled simultaneously as a single integrated system, see Fig.1. Designing a unified model-based controller for this type of configuration is theoretically challenging, while practical implementation depends on the onboard computational capabilities of the system [14]. Next, the specific types of developed controllers are discussed.

1) Linear Controllers: Derivation and implementation of linear controllers for fully coupled multirotor-manipulator systems reveal challenges in managing complex dynamic interactions and tightly integrated subsystems. Lack of any experimental demonstrations further supports this observation. For example, in [15] a helicopter that is equipped with a 1-DoF arm (featuring a heavier structure compared to typical arms), demonstrates low position error in simulation studies. However, it should be noted that the implemented LQR controller is designed for the linearized system, while the full dynamics of the system exhibit high computational complexity, making real-time implementation very challenging.

2) Nonlinear Controllers: Several nonlinear controllers have been developed and implemented for fully coupled multirotor-manipulator schemes, which also include partially decoupled dynamics [13][16][17] or quasi-static motion [18] to overcome the computational burden.

Door opening tasks are demonstrated in a lab experiment using a MPC with a disturbance observer-based framework [18]. The coupled system highlights minimal position errors (< 2cm). However, it is mentioned that faster door movement, caused by uncertainties in door parameters and unmodeled dynamics between the UAM and the door, may lead to detachment of the end-effector from the door surface. This issue can be potentially addressed using impedance control. Research in [13] uses passive decomposition to decouple system dynamics into center-of-mass translation and internal rotation, employing a backstepping-like controller for exponential stability.

More recent work demonstrates adaptation to external disturbances in outdoor environments [16], or simultaneous trajectory tracking and aerial manipulation [17]. In [16] the task of picking an object is successfully achieved under geometric control (along with Center of Inertia (COI) modeling and SE(3) dynamics); however, the position error is approximately 50 cm, which may become even larger in more dynamic environments or under windy conditions. In [17], a multi-stage MPC is proposed, effectively decoupling the multirotor and manipulator dynamics, yet enabling a hierarchical control structure that reduces computational complexity while addressing coupling effects incrementally. While the computational complexity is reduced compared to single-stage MPC approaches (assumptions of simplified dynamics and constant disturbances), real-time implementation on resource-limited systems remains challenging.

3) Robust Controllers: Robust controllers of multirotor-manipulator systems have demonstrated high precision when testing disturbances within predefined limits [19] or evaluating torque disturbances [20]. Authors in [20] propose a robust control strategy for a hex-rotor UAV equipped with a 2-DoF manipulator. Coupling effects are addressed through a dynamic model with variable inertia parameters. By implementing a disturbance estimator and H_∞ compensator, the approach effectively mitigates external forces and torque disturbances. Experiments confirm enhanced position and attitude accuracy, particularly in the X and Y directions, with the applied disturbance compensation.

While most research on multirotor-manipulator systems has utilized fixed-propeller configurations, tilting mechanisms are increasingly applied for real-time contact interactions with rigid arms [21]. For example, a tilting omnidirectional quadrotor equipped with a 6-DoF arm is investigated in [19] and the super-twisting sliding mode control (STSMC) proposed by the authors demonstrates low norm error, yet in simulations.

4) Adaptive Controllers: Adaptive controllers in fully coupled multirotor-manipulator schemes exhibit high precision and medium complexity [22][23][24], opening the road for real-time implementation scenarios. For example, in [22] the quadrotor and the 2-DoF arm are considered as a combined system. The task succeed to perform pick-up of a wooden block (0.45kg) with a low position error; that is 2.0-2.5 cm. The adaptive sliding mode controller showed robustness to uncertainties (i.e., unknown mass and inertia of the object). Higher DoF manipulators (i.e., 6DoF) also tested under adaptive control but with a reduced regression (i.e., account only for gravity) [25]. Simulation experiments showed high accuracy in steady-state-errors but large transient errors made authors comment on using the whole regressor instead. A passivity-based adaptive controller [23] is developed to ensure stability and robustness against modeling uncertainties, with an adaptation law for estimating unknown parameters. The authors highlight a key simplification; the omission of $\hat{C}\dot{q}_r$ (i.e., rate of change of Coriolis effects) in the control law, arguing that it simplifies computation without compromising performance during hover flight.

5) Impedance Controllers: Impedance controllers demonstrate high precision in more complex contact tasks [7] and in the presence of external disturbances [26]. However, along with assumptions as aerodynamics forces negligible and slow speed motion.

Specifically, in [26], two simulated case studies (i.e., under external disturbances and point contact) have been developed so as to give insights about the dynamic relationship between external generalized forces acting on the structure and the whole system's motion. Also, rigid and compliance behavior is investigated under impedance control; the latter showed larger position error, although provides adaptability. In [7] authors employ impedance control to manage the interaction between the 6-DoF manipulator and the environment (i.e., a small rig for peg-in-hole task), ensuring stability during the transition from free motion to contact.

6) Hybrid Controllers: Hybrid controllers are widely applied from recent works [27][28][29][30] when considering fully coupled control schemes. Although, mostly demonstrated in simulations [28][29][30] or for simple tasks [27].

By addressing the strong dynamic coupling disturbance problem of the aerial manipulation system [27], authors consider the full dynamics of UAV and manipulator. Control scheme involves cascaded PID and Adaptive Neural Network Backstepping (ANNB) controllers, enhanced by feedforward compensation; this method effectively mitigates coupling disturbances by leveraging precise dynamic modeling with variable inertia parameters. The results highlight superiority (i.e, ANNB in handling nonlinearities, feedforward compensation reduces tracking errors, high-speed manipulator motion) to traditional methods (i.e., PID, robust DOB, robust ESO).

The combined system of [28] applies a hybrid approach; an adaptive Nonsingular Fast Terminal Sliding Mode Control (ANFTSMC) with a nonlinear disturbance observer (NDO). While this method improves trajectory tracking for aerial manipulators under disturbances, it assumes bounded disturbances, which may limit robustness in dynamic environments. Hybrid approach also employed in [29]. Authors use an Adaptive Incremental Nonlinear Dynamic Inversion (INDI) controller with a Kalman filter for real-time control effectiveness estimation, eliminating the need for prior knowledge of the manipulator's mass or inertia, ensuring adaptability to dynamic changes. However, the real-time implementation of this method presents challenges due to its computational complexity and reliance on precise sensor measurements, which could limit its feasibility on UAVs with constrained processing capabilities.

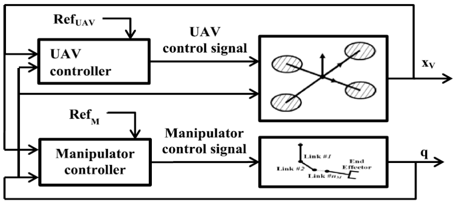

Fig. 2. Scheme of partially coupled UAM control [14] - Ref_{UAV}, Ref_M (desired states), x_v, q (state feedback)

B. Partially Coupled

The aerial platform and manipulator are controlled separately, yet their controllers utilize data from both systems to estimate interaction forces and enhance the overall performance of the integrated system (i.e., shared feedback) [14][9], see Fig. 2.

1) Linear Controllers: Linear controllers are dominant in partially coupled control schemes; the simplicity in dynamics is translated into easier implementation and reduced computational complexity.

Several multirotor-manipulator systems are validated in simulation [31][32][33]. These studies focus on relatively simple experimental tasks (i.e., stabilization, trajectory tracking), yet more dynamic interactions could potentially degrade performance. For example, in [31], a PD/PID control approach for a UAV and 2-DoF arm performs well in simulation but may degrade in realistic scenarios due to inertia and center of mass variations. Similarly, [32] uses a force control strategy with feedback linearization to minimize end-effector position errors. In [33], a hierarchical framework combines inverse kinematics for motion references with cascaded UAV control and a model-based torque controller for precise manipulator joint control.

From the other hand, lab experiments demonstrate high precision of the end-effector under significant external disturbances (i.e., up to 6m/s) [34]. This is achieved through a composite anti-disturbance scheme combining a joint velocity planner for disturbance mitigation and a dynamic controller to handle coupling and model uncertainties. Also, neural network approximation simplifies dynamic coupling and estimates unknown nonlinear terms, maintaining a position error of about 4.5cm. Real-time push and slide operations for inspection tasks [35][21] use tilted-propeller multirotors with multi-DoF arms. In [35], a displaced PID-based controller with a mixed feedback strategy (position and force feedback) ensures precise control and stability by compensating for arm elasticity and external disturbances. However, the experiments is held near quasi static conditions. Authors in [36] further extend their previous work [37] by accounting kinematic and dynamic coupling of both controllers to increase performance. While the approach effectively manages CoG adjustments to maintain system stability and relaxes from assumptions such as low speeds, authors mention that may be insufficient for more complex manipulations.

2) Nonlinear Controllers: Focusing on real-time experiments, nonlinear controllers address the challenges of dynamic interactions and environmental disturbances while successfully operating outdoors and handling object manipulation tasks with payloads of up to 1 kg [38]. However, implementation complexity increases.

Authors in [39][40] designed a system for outdoor operations; an octocopter equipped with a 7-DoF arm. The control framework tackles multirotor-manipulator coupling challenges, including center of mass shifts, inertia variations, and reaction forces. A Variable Parameter Integral Backstepping (VPIB) controller stabilizes the octocopter, while an admittance controller governs the manipulator. High-accuracy sensors like RTK-DGPS and cameras ensure precise positioning, demonstrating real-time feasibility. Nonlinearities introduced by using elastic joints instead of rigid ones are addressed in [41], which incorporates mechanical compliance to effectively absorb internal interactions during aerial physical interaction tasks through an optimal control strategy. Compliance is also addressed in human-UAV interactions [42].

The control framework in [38] addresses pick-and-place missions using a quadcopter with a 2-DOF manipulator extending over twice the UAV's radius. A partially coupled scheme uses Model Predictive Control (MPC) to optimize trajectories by accounting for UAV-manipulator interactions, reducing object retrieval time from 15 to 5 seconds, while feedback linearization and PID control mitigate MPC's high computational demands.

3) Adaptive Controllers: Unlike fully coupled control, where adaptive controllers are commonly used, partially coupled schemes rarely employ them due to the strong dynamic coupling, which can hinder the adaptive behavior of the system and limit its ability to achieve greater integration between subsystems.

Nevertheless experiment in [43] achieves object manipulation with high precision (most examples focus on pick-and-place operations or simple trajectory tracking). Authors present an adaptive control strategy combining PD control for quadrotor attitude stabilization with an adaptive position controller for trajectory tracking, while the manipulator is handled using independent joint PID control, simplifying the system by modeling it as an open-chain mechanism and approximating payload disturbances as basic forces. Focusing on balancing dynamic couplings using adaptive control laws, authors in [44] adopt a modular control approach. While the dynamic modeling remains fully coupled, the control law decouples the system due to complexity considerations; the adaptive gains for each subsystem are computed independently.

4) Robust Controllers: Robust controllers are adopted by recent works in partially coupled category. Authors in [45] demonstrate two laboratory experiments: pick-and-place of an egg and pushing a button, highlighting the dexterity of the custom 6-DoF manipulator. The manipulator features innovative designs, including a bird-inspired structure, three soft fingers on the end-effector, and a telescopic joint. A refined Anti-Disturbance Controller (RADC) is employed to mitigate multi-source disturbances, utilizing a partially decoupled dynamic approach. The authors suggest that future work will address additional uncertainties to further enhance the system's robustness and adaptability.

5) Vision-based Controllers: Vision-based controllers represent a significant step toward fully automated operations; however, their complexity increases due to the need for real-time image processing, integration with control algorithms, and managing uncertainties in visual feedback.

Authors in [46] propose an hierarchical control strategy that prioritize tasks; an image-based visual servoing (IBVS) with manipulator-specific tasks like CoG alignment and joint-limits avoidance. The hierarchical approach prioritizes the visual servo task, with secondary tasks managed through null-space projections to prevent interference. While the IBVS and PD controller for the manipulator share some information, they operate semi-independently. Although the strategy demonstrates successful results, the complexity of the hierarchical design may pose challenges for real-time applications. Hierarchical task prioritization with visual servoing also proposed in [47], focusing on the simultaneous control of a UAV and its attached robotic manipulator. The framework integrates a task-priority approach to decouple and prioritize various subtasks, such as gripper positioning, orientation, and maintaining the UAV's stability. Visual servo control for aerial manipulation using a spherical projection model is proposed in [48]. Outdoor experiments proved successful, however, the authors acknowledge the challenge of time delay in the feedback loop, proposing the need for future research to formally address its impact on system performance.

6) Learning-based Controllers: Learning-based controllers in aerial manipulation offer the potential to address the complexities of dynamic coupling between UAVs and manipulators by adapting to non-linear interactions and unpredictable environmental disturbances. While still relatively uncommon in the literature, these methods hold the potential to enhance precision and robustness in dynamic tasks while reducing dependency on simplified models.

A learning-based adaptive controller is presented in [49], discussing multi-task aerial manipulation (i.e., peg-in-hole and hanging tasks through two different arms) and energy-efficiency showcasing position error less than 5cm. The framework integrates a reduced-order Single Rigid Body (SRB) model for trajectory planning, treating quadrotor and manipulator dynamics separately but accounting for their interaction through disturbance terms. A neural network, trained offline in 10 minutes, adaptively predicts and compensates for these manipulator-induced disturbances, ensuring precise control and robust adaptation to varying arm configurations and payloads. The arm employs impedance control facilitating smooth robotic arm movements, while polynomial trajectory planning enhances energy efficiency and stability for the UAV and manipulator.

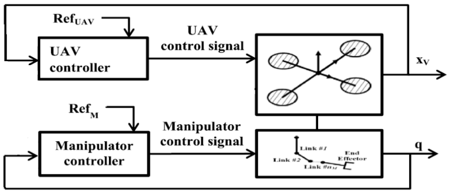

Fig. 3. Scheme of decoupled UAM control [14] - Ref_{UAV}, Ref_M (desired states), x_v, q (state feedback)

C. Decoupled

In decoupled control, see Fig. 3, the aerial vehicle and the robotic arm are treated as separate subsystems, each controlled independently. The decoupled strategy assumes that the manipulator's impact on the aerial platform's attitude and position dynamics is minimal. Consequently, dynamic coupling is either ignored or, at most, considered as a disturbance to be compensated for; the effect of the manipulator is not explicitly taken into account in controller design. This assumption drives the development of lightweight [50], low-inertia manipulators [9]. Decoupled control methods are most effective during quasi-static motions; when the motion involves higher acceleration demands, these methods either fail or result in significant tracking errors.

1) Linear Controllers: Linear controllers are commonly utilized in decoupled control schemes as the absence of strong dynamic coupling simplifies their implementation. However, this simplicity comes at the cost of limited capability to handle complex tasks that require dynamic interactions.

Several works [51][52][53] consider the arm as a disturbance to the overall system. For example, sequential aerial manipulation [51], dynamic grasping [52] and coupling disturbances compensation [53] are handled under PID controllers, but with limited experimental validation or reliance on simplified dynamics.

Conversely, in works of [37][54][55][56][57], the arm is controlled in a fully independent manner. For example, position controller for a helicopter and an admittance control scheme for a 7-DoF arm are demonstrated in outdoor environments to perform grasping tasks [37]. Although this work showcases a practical experiment, the coupling between the helicopter and the arm is neglected, leading to slow-speed operations. Similar experiment on testing compliance is demonstrated in [54]. In [55] authors present an alternate configuration; the arm is not located at the center of mass, instead is positioned at the front, while the battery is placed at the back to counteract the resulting imbalance. Leveraging differential flatness, the system achieves smoother dynamics and simplified trajectory generation, with a cascaded PID controller enabling accurate, real-time control for simple tasks in low-disturbance environments and operational times up to 20 minutes. PID control method also employed in [56]. Nevertheless, authors acknowledge that the decoupled control scheme significantly impacts the system's overall precision and reliability. This limitation arises from the lack of feedback integration, which restricts the manipulator's ability to adjust dynamically to positional errors during the object's retrieval process. In [57], the authors propose a multilayer control approach for the multirotor-manipulator system, integrating dynamic and static compensation to address CoG shifts and manipulator gravity effects. While effective, the multilayer architecture adds complexity, potentially affecting real-time performance and scalability in dynamic tasks.

2) Nonlinear Controllers: Nonlinear controllers are not so commonly used in decoupled control multirotor-manipulator schemes, likely because the simplified dynamics of decoupled systems reduce the necessity for advanced techniques. Nevertheless, works as [19][58] showed high precession in their experiments. The second part of [19] explores human-UAV interaction, utilizing a classical quadrotor instead of the omnidirectional multirotor used in the first part of the paper. The focus is on geometric control of the UAV, operating directly in SE(3) space to simplify the control law by leveraging spatial relationships, while the arm functions under admittance control. However, the modeling approach assumes perfect actuator responses and limited dynamic coupling, potentially limiting robustness in highly dynamic environments.

3) Hybrid Controllers: Experimentation on hybrid control approaches demonstrate successful multi-task collision avoidance experiment [59]. Similar to [49], yet with a decoupled control scheme; the arm's influence acts as a disturbance to the system. The UAV and manipulator are treated as separate entities; an adaptive backstepping controller stabilizes the UAV while compensating for disturbances caused by the manipulator, and a dedicated manipulator controller ensures precise end-effector trajectory tracking while handling subtasks like Joint Angle Limitation (JAL) and Obstacle Avoidance (OA).

III. CONCLUSIONS AND DISCUSSION

This survey summarizes published research in aerial manipulation focusing on individual control strategies that are suitable for real-time implementation.

Table I presents the results of the comparative study. Precision is classified as low for errors above 10 cm, medium for 5–10 cm, and high for errors below 5 cm or when the task is completed with minimal transient errors and a well-followed trajectory. Robustness indicates testing under uncertainties or external disturbances. Implementation complexity is determined by trade-offs between simplicity, robustness to disturbances, and scalability. This process involves evaluating key factors such as the design of the control architecture (including the use of estimation techniques and sensor fusion), simplifications or assumptions in order to reduce dynamic complexity, the computational resources required (e.g., optimization or iterative processes) and experiment deployment.

Coupled control schemes in multirotor-manipulator systems exhibit high precision yet involve significant implementation complexity due to the interdependent dynamics of the subsystems. Authors to address this challenge by adopting partially decoupled dynamics or low-DoF designs to reduce

TABLE I

SUMMARIZING TABLE OF AERIAL MANIPULATION SYSTEMS WITH MULTI-DOF ARMS: CONTROL STRATEGIES

Ref	Platform	Control	Modeling	Assump./Simpl.	Precision	Impl. Comp.	Robustness	Weight	Task	Exp/Sim
COUPLED										
[22]	Quad + 2DoF arm	Adaptive Sliding Mode Controller	EL	- Small roll/pitch angles - Known object position via Vicon - Neglect of higher-order effects - Simplified adaptation dynamics - Hardware-dependent constraints	High	Medium	Yes	0.45kg	Pick and place	Lab Exp
[25]	Quad + 6DoF arm	Adaptive	RNE	-Reduced regression (account only gravity)	High	High	Yes	-	Stability	Sim
[26]	Quad+3DoF arm	Impedance	EL	-Aerodynamic forces negligible -Low speeds	High (rigid)/ Low (compliance)	High	Yes	-	External disturbance, Point contact	Sim
[23]	Hexa+3DoF arm	Passivity-based adaptive	EL	-Small angle -Δ changes slowly	High	Medium	Yes	0.16kg	Pick	Lab exp
[7]	Quad+6DoF arm	Impedance	NE	-Neglect aerodynamic -Simplified arm model -Low speeds	High	High	Yes	Not reported	Peg-in-hole	Lab exp
[13]	Quad+2DoF arm	Backstepping	EL	-Decoupled dynamics -No Coriolis - Simplified gravitational effects	Medium	Medium	No	-	Trajectory tracking	Sim
[15]	Heli+1 DoF arm	LQR	EL	-Neglect higher-order nonlinear aerodynamic effects	High	Medium	Yes	-	Trajectory tracking	Sim
[20]	Quad+2DoF arm	Hinf	NE	-Inertia parameters estimated -Decoupled dynamics	High	Medium	Yes	-	Test torque disturbances	Lab exp
[18]	Hex+4DoF arm	MPC	EL	- End-effector rigidly attached to door - Physical properties of the door are known and constant - Quasi-static state - Multirotor's rotational dynamics negligible	High	High	Yes	11kg	Push	Lab exp
[27]	Hexa+4DoF arm	Cascaded PID and adaptive neural network backstepping (ANNB)	NE	-Small pitch and roll angles -UAV axisymmetric -CoM constant	High	High	Yes	-	Trajectory tracking	Lab exp
[24]	Quad+ 3DoF arm	Adaptive	NE	- Prior knowledge of disturbance boundaries not required	High	Medium	Yes	-	Trajectory tracking under disturbances	Lab exp
[17]	Quad+ 3DoF arm	MPC	EL	- Neglecting Higher-Order Nonlinearities - Bounded Disturbances - Constant Disturbances in Future Steps - Fixed Manipulator Configuration	High	High	Yes	-	Trajectory tracking and grasping under disturbances	Sim
[30]	Quad+ 2DoF arm	ESO and Control Lyapunov Function	EL	- Input-to-State Stability (ISS)	High	High	Yes	-	Trajectory tracking under disturbances	Sim
[28]	Quad+ 2DoF arm	Adaptive Nonsingular Fast Terminal Sliding Mode Control (ANFTSMC)	EL	- Neglecting High-Frequency Chattering - Bounded disturbances	High	High	Yes	-	Trajectory tracking	Sim
[29]	Heli+3DoF arm	Adaptive INDI with PID	NE	-Aerodynamic forces and torques negligible -Gˆ-1 matrix simplified -Time scale separation	High	High	No	1kg	Pick/Helical Trajectory tracking with object	Sim
[16]	Hexa+ 2DoF arm	Geometric	NE	-COI avoids coupling	Medium	High	Yes	170gr	Pick with disturbances	Out exp
[19]	Omnidirectional tilting quad + 6DoF arm	Super-twisting sliding mode control (STSMC)	NE	- Known system dynamics -Disturbances to predefined limits - Higher-order dynamic effects negligible	High	Medium	Yes	2.2N	Trajectory tracking and force on surface	Sim
PARTIALLY COUPLED										
[33]	Quad+ 5DoF arm	Cascaded+torque	EL	-Noise-Free Conditions -Low speeds -Aerodynamic effects negligible	High	Medium	Yes	-	Trajectory tracking	Sim
[39]	Octo+7DoF arm	Backstepping+admittance	EL	-	High	High	Yes	-	Hover	Out EXP
[42]	Quad+ 2DoF arm	QP-based with PID+torque	RNE	-Constraints (e.g. avoiding singularities)	High	Medium	Yes	-	Navigation/Compliance	Lab exp
[38]	Quad+ 2DoF arm	MPC+PID	NE	- Reduced real-time feasibility -Decoupled dynamics	Medium	High	Yes	1kg	Pick and Place	Lab exp
[31]	Quad+ 2DoF arm	PD+PID	RNE	-Ideal conditions (e.g. no external disturbances) Decoupled/Simplified Dynamics -Higher-order nonlinear effects neglected	High	Low	No	-	Hover and Stabilization	Sim
[49]	Quad+ 3DoF arm	Adaptive+Impedance	NE	-Decoupled/ pre-determined dynamics - Spring-mass manipulator and single rigid body assumptions -Pre-collected training data -Simplified control laws	High	High	Yes	0.6kg	Peg-in-hole and hang	Lab exp
[32]	Quad+ 2DoF arm	PD+ trajectory tracking	RNE	- Decoupled/Known dynamics -Small-angle approximations - Predictable reaction forces	High	Low	No	-	Force on end-effector	Sim
[43]	Quad+ 2DoF arm	Adaptive/PD +PID	RNE	-Known object position -Negligible aerodynamic effects -Robotic arm modelling simplifications (e.g.Rotational Joint Dynamics only)	High	Low	No	Not reported	Object manipulation	Sim
[41]	Quad+2DoF arm	Position+optimal control	Second-order LTI model	- Small pitch and roll angles -Negligible damping effects -Motor as ideal velocity source	Medium	Medium	No	-	Force at surface	Lab exp
[22]	Quad+6DoF arm	Image-based+PD	EL	-Approximations in image Jacobian computation	High	High	Yes	-	Trajectory tracking	Lab exp
[35]	Hexa+2 DoF arm	PID+PD	EL	-Slow speeds -Dynamic couplings neglected	Medium	Low	Yes	-	Push and slide	Lab exp
[47]	Octo+6DoF arm	Visual servoing+task priority	Jacobian-based	-Time-scale separation -Assumption of full rank Jacobian	High	High	No	Not reported	Grasp and plug	Lab exp
[36]	Heli+7DoF arm	Orientation controller+impedance	NE	-Simplified model -Ideal manipulator controller	Medium	Low	Yes	Not reported	Pick and release	Out exp
[44]	Quad+2 DoF arm	Adaptive+Joint	EL	- State-Dependent Uncertainties -Inertia coupling not considered in model -Known bounds	High	Low	Yes	0.2kg	Pick and place	Lab exp
[48]	Quad+4 DoF arm	Task priority control +visual servo	EL	- Spherical projection model	High	High	Yes	Not reported	Pick	Out exp
[34]	Quad+5 DoF arm	PID/PD+dynamic composit controller	NE	- Neural Network (NN) approximation	High	High	Yes	Not reported	Pick under disturbances	Lab exp
[45]	Quad+6 DoF arm	Anti-disturbance controller (RADC)/Joint	NE	-Part of dynamics decoupled - Perfect actuator responses - Predictable disturbances	High/Medium	Medium	Yes	Not reported	Pick and place/Push	Lab exp
DECOUPLED										
[59]	Hexa+3DoF arm	Adaptive backstepping	NE	-Small roll and pitch angles -Decoupled/Known dynamics -Higher-order coupling effects negligible -Simplified geometric constraints for subtasks	High	Medium	Yes	-	Collision avoidance	Lab exp
[52]	Hexa+3DoF arm	PID	NE	-Known dynamic parameters, e.g. inertia -Simplified coupling -Control assumptions, e.g., idealized model for grasping, simplified jacobian	Medium	Low	No	0.35kg	Dynamic grasping	Sim
[37]	Heli+7Dof arm	Position controller+Impedance	NE	-Decoupled dynamics -UAV dynamics simplified -Low-speeds -Fixed external conditions	Medium	Low	Yes	Not reported	Pick	Out exp
[54]	Octo+6DoF arm	Position controller+Impedance	NE	-Aerodynamic effects negligible - Decoupled/Known dynamics	Medium	Medium	Yes	Not reported	Pull and Push	Lab exp
[57]	Octo+6DoF arm	PID+PID	NE	- Partly aerodynamic effects negligible - Simplified multirotor dynamics	High	Medium	Yes	-	Stability and compensation	Lab exp
[55]	Quad+5DoF arm	Cascaded PID+joint controller	NE	-Thrust and torque serve as control inputs	High	High	No	Not reported	Pick	Lab exp
[53]	Quad+2DoF arm	GS PID	-	-Quasi static	High	Low	No	-	Hover and arm movement	Lab exp
[56]	Quad+2DoF arm	PID+ Open-loop inverse kinematics	-	- Simplified control (open-loop)	Low	Low	Yes	100gr	Pick and Place	Lab exp
[51]	Four thrust generators +3DoF arm	Hierarchical controller with PID	NE	-Simplified dynamic model - Virtual Kinematic Chain (VKC) for manipulator	High	High	No	Not reported	Open/close drawer, pick object	Lab exp
[19]	Quad+6DoF arm	Geometric+admittance	Geometric modelling SE(3)	-Disturbances within bounds -Idealized human interaction	High	Medium	Yes	1.4N	Human-UAV interaction	Sim
[58]	Quad+3DoF arm	Prescribed performance	RNE	-Small roll and pitch angles - Modeled as reduced-order model -Bounded disturbances	High	Low	Yes	-	Trajectory tracking	Out exp

complexity, especially in nonlinear methods. Experiments with impedance controllers demonstrate their effectiveness in managing fully coupled dynamics and higher DoFs, achieving precision but at the cost of increased complexity and low speeds. The intricacy of such systems leads to the use of hybrid methods, as found in newer works, to better address their inherent complexity or to the adoption of a partially coupled approach. Such methods relax from strong coupling and demonstrate variety and experimentation, mostly in linear and non linear methods. From the other hand, decoupled control strategies are preferred for their simplicity, as they neglect coupling effects, but this often results in low precision in dynamic tasks. While there are methods that achieve higher precision with moderate to low implementation complexity, they are usually tested in controlled environments with minimal disturbances or in simple tasks requiring limited dynamic interaction and operating at low speeds. The choice of hardware, whether off-the-shelf or custom-built, can further influence implementation complexity. Linear controllers dominate due to simplified models and negligible aerodynamic effects, with successful tests in lightweight payload experiments on 6- or 7-DoF systems. Nonlinear and hybrid methods, though promising in simulations, remain underexplored in real-world dynamic tasks, where successes are mostly seen when the robotic arm is treated as a disturbance to the UAV.

A. Future Directions

Research in controller designs for multirotor-manipulator systems faces open challenges in balancing advanced methods as nonlinear, data-driven, model-based, and learning-based approaches while addressing trade-offs between simplicity, precision, and computational complexity. Effective designs must handle factors like wind disturbances, varying speeds, and non-ideal experimental conditions, often requiring simplified assumptions for unknown system parameters. Precise control of aerial manipulators is restricted by model uncertainties and strong internal coupling, especially in multi-joint systems where dynamic uncertainties are amplified by complex coupling effects.

Authors favor quadrotors for their hardware simplicity, but their limited payload capacity restricts demanding tasks. Similarly, while multi-DoF arms offer flexibility, they typically handle objects under 1kg, limiting practical use. Dual arms or cooperative aerial manipulation [10] might solve these challenges. In the literature, dual-arm configurations are often implemented in decoupled schemes [60][61] or partially coupled [62]; this translates to further investigation into their impact during dynamic tasks. Custom designs also restrict the ease of deployment.

Autonomous navigation in unknown environments is critical for real-time applications, yet strongly increases computational costs. Experiments in lab and outdoor conditions are present but often implemented within bound disturbances, idealized conditions and motion capture systems. Time-delay in high frequencies and safety are also some aspects that need to be addressed in the future.

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