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Review of Aerial Manipulator and its Control

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ABSTRACT

The aerial manipulator is a new type of aerial robot with active operation capability, which is composed of a rotary-wing drone and an actuator. Although aerial manipulation has greatly increased the scope of robot operations, the research on aerial manipulators also faces many difficulties, such as the selection of aerial platforms and actuators, system modeling and control, etc. This article attempts to collect the research team's Achievements in the field of aerial robotic arms. The main results of the aerial manipulator system and corresponding dynamic modeling and control are reviewed, and its problems are summarized and prospected.

1. Introduction

In the past few decades, due to the advantages of avoiding casualties, high performance, and strong adaptability to harsh environments, unmanned aerial vehicles (Unmanned Aerial Vehicles) have played an increasing role in various fields, especially multi-rotor unmanned vehicles. Due to its simple structure, low cost, and strong functionality, the aircraft is used in many non-contact operations, such as aerial photography, surveillance, inspection, and patrol. In 2016, the National Science Foundation (NSF) provided US$35 million in research funding in the next five years to accelerate the development of drone design and control, such as physical infrastructure monitoring and inspection, intelligent disaster response, agricultural surveillance, and other fields. New York State made a down payment of $5 million to support the development of the emerging UAV industry throughout New York. But with the increasing demand, drones need to complete the task of physically interacting with the environment. The multi-degree-of-freedom air manipulator consists of an airplane, and a multi-degree-of-freedom manipulator mounted on the airplane. The aerial manipulator improves the maneuverability of the manipulator and also enhances the function of the aircraft. Therefore, in recent years, aerial manipulators have attracted the attention of many researchers. Aerial manipulate generally refers to the activities of grasping, transporting, positioning, and measuring an aircraft with the ability to hover by using an end-effector or gripper installed on the aircraft. Encourage the physical interaction between the drone and its surrounding environment, enabling the drone to perform a whole new range of tasks. As the introduction of

the robotic arm increases the degree of freedom, it expands the drone's ability to complete complex tasks from non-contact tasks (such as inspection, mapping, remote monitoring, etc.) to contact tasks (such as cutting high-voltage cables, transporting packages, bridge inspections, etc.).

Aerial manipulation is a new research field. In the past decade or so, aerial maneuvering has included a gripper rigidly attached to the drone's fuselage or based on a tethered configuration. In recent years, some more challenging problems have been solved, such as power line inspection [1], wind turbine maintenance [2], Grab moving objects [3].

Aerial manipulators can be deployed in remote areas or hard-to-reach places for inspection and maintenance [4][5]. Fig. 1 shows some example scenarios where integrated management systems can be used, including the insulation of wind turbine blade cracks, the cleaning of plugged thermocouples on industrial chimneys and bridges. Contact inspection with dams, placement, and recovery of smart sensors in large areas and infrastructure [6]. In [7] introduced the design, development, and prototype development of a new type of aerial interception manipulator, which is composed of a single degree of freedom (DoF) manipulator and a passive basket end effector.

Fig. 1. Application examples of aerial manipulators [6]

Due to the introduction of actuators, the autonomous control of operational flying robot systems faces obvious difficulties. First of all, the motion mechanism of the rotary-wing flying robot system is to rely on the high-speed rotation of the rotary-wing to generate the relative motion between the airflow and the body and thereby generate the power of the robot movement. This force generation mechanism causes the rotary-wing flying robot system to show obvious strength—linearity, large coupling, under-driving, and other characteristics, and very sensitive to external disturbances. Due to the different dynamic couplings between the aircraft and the robotic arm, the control and stability of the aerial system composed of a helicopter or multi-rotor and the robotic arm are very complicated. In addition, when the arm grasps and manipulates objects, the dynamic characteristics of the vehicle will also change. This is because the mass center and mass distribution of the aircraft are changed by grasping and manipulating objects. Similarly, the contact force that occurs when interacting with the environment may have an additional effect on the dynamics. When the actuator is installed, the coupling effect between its four-rotor UAV system will greatly increase the complexity of its dynamic characteristics and bring great difficulties to the modeling and control of the system. And the contact between the operational aerial manipulator and the external environment is indispensable, so the following two problems will make the control difficult: 1) When the aerial manipulator system is close to an external object, the surrounding airflow movement will make

the rotor air The dynamic parameters change, which leads to the uncertain movement of the operated target; 2) When in contact with the environment, the system will inevitably continue to be affected by external force/torque disturbances, such contact forces under rigid position constraints / Torque disturbance will have a significant impact on the motion characteristics of the aerial manipulator [8].

In the face of these problems, this article reviews the research results of aerial manipulators in recent years from the aspects of aerial platform, manipulating device, modeling, control, etc., and conducts in-depth analysis and prospects of the basic problems in the research.

2. Aerial Platform

Due to the large number of applications of UAVs, it is difficult to accurately classify UAVs because there are many devices of different sizes and mechanical configurations on the market. UAVs can be divided into the following five categories according to the configuration of the flight platform:

1) Multi-rotor UAVs, also known as vertical take-off and landing UAVs, have the advantages of hovering in the air and high mobility. Rotor UAVs have traditional helicopter configurations, namely main rotor and tail rotor, as well as coaxial rotors, two rotors, multi-rotors, and many other configurations.

2) Parafoil UAV, also known as unmanned powered parafoil, is composed of ram parafoil and power unit. Although the take-off and landing roll distance are short, it is difficult to overcome the influence of airflow.

3) Flapping-wing UAVs have wings that are as flexible as insects or birds. There are also other hybrid or deformable configurations. It can take off vertically, tilt and rotate, and fly like an airplane.

4) Fixed-wing UAVs refer to UAVs that need to take off and land through the runway. This means that UAVs generally have a longer flight time and a higher cruising speed.

5) Aircraft that are lighter than air, such as autonomous airships. However, airship systems are currently not commonly used, mainly because of their low payload volume ratio, high air resistance, sensitivity to aerodynamic interference, and lack of proper infrastructure for operation.

UVS-International has classified UAVs as shown in Table 1.

Table 1. UAV categories defined by UVS International

Number	Classification	Mass (kg)	Range (km)	Flying height (m)	Endurance (hours)
1	tiny	<5	<10	250	1
2	Small size	<25/30/150	<20	150/250/300	<2
3	small range	25-150	10-30	3000	2-4
4	Medium range	50-250	30-70	3000	3-6
5	high altitude	>250	>70	>3000	6

In most cases, aerial robots correspond to the miniaturized version of manned aircraft in one way or another. Relatively classic fixed-wing unmanned aerial systems and rotary-wing unmanned aerial systems are shown in Fig. 2. They are common flight configurations that may be encountered in most applications, including surveillance, inspection, mapping, or payload transportation.
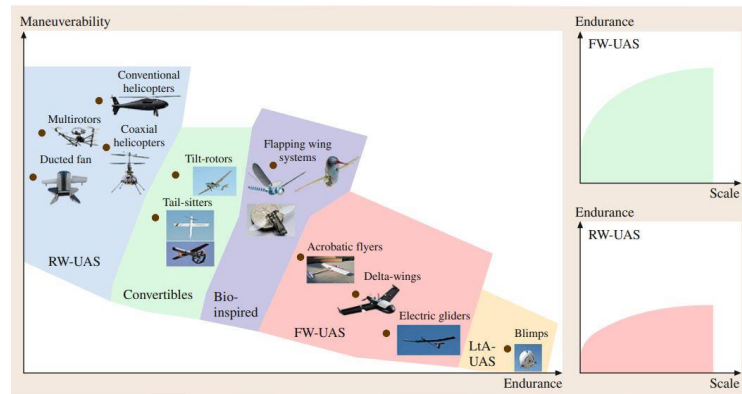
Fig. 2. Aerial platform classification [9]

Multi-rotor UAVs, helicopters, and fixed wings are all aerial platforms with autonomous flight capabilities, but not all of them are suitable for aerial control. Since helicopters and multi-rotors have fixed-point hovering capabilities, this is something that fixed-wing UAVs cannot do because they need to maintain a minimum forward speed, so they are not discussed in this article. In the following, the author will introduce rotor drones, helicopters, and new aerial platforms according to classification.

2.1. Multi-Rotor Platform

Multi-rotor is the most frequently discussed aerial platform for aerial control, and it has also become the standard platform rotary-wing drone for navigating in three-dimensional space. Multi-rotor drones are also called vertical take-off and landing drones, which are heavier than air. Its lift in the air is obtained by the reaction of the relative motion of multiple rotors with the air. The hovering capability of the multi-rotor aircraft provides an opportunity for the drone to keep flying in the air, and any manipulator connected to it can perform useful maneuvers. According to the number of rotor arms, the direction of the rotor arms, the number of propellers in each arm, and the propeller configuration, there are multiple configurations of multi-rotors. Regarding the number of arms, the most popular are four-rotor and six-rotor.

The quadcopter is currently the most widely used drone operating platform, followed by small helicopters. This is mainly due to the simplicity of the mechanical design and hovering capabilities of the quadcopter, as well as the low cost, the agility of these aircraft, and the addition of existing precise control schemes. Quad-rotor drones are very suitable for aerial maneuvering or grabbing tasks. However, there are three main challenges to overcome: precise positioning, object sensing and manipulation, and stability in the event of interference caused by object interaction.

Compared with other UAV structures, quadrotors have higher motion capabilities, so researchers are interested in using quadrotors with interactive tools connected to the system for aerial maneuvering tasks. This configuration can expand the capabilities of mobile robot systems and provide opportunities for new applications for quadrotors.

Trujillo MA et al. [10] proposed a bird-inspired flying autonomous grasp. The experiment was carried out on a quadrotor. The quadrotor is equipped with a drive attachment that can grasp and retrieve objects at speeds of 2 m/s and 3 m/s. Xiangdong Meng et al. [11] developed an aerial manipulator system composed of a six-rotor drone and a single-degree-of-freedom manipulator, which is used to turn off the machine by pressing the emergency switch in an emergency. It can be shown in Fig. 3.

2.2. Helicopter Platform

Unmanned helicopter refers to vertical take-off and landing (VTOL) unmanned aircraft that can fly remotely by radio or autonomous air flight. It is a rotary-wing aircraft in terms of

structure and a vertical take-off and landing aircraft in function. They are mainly used for reconnaissance and data collection missions, surveillance, and hazardous area applications. In order to take off and land autonomously, most aircraft are equipped with inertial measurement units, and many aircraft are also equipped with global positioning system receivers and cameras. In the past ten years, with the research and development of flight control technology, unmanned helicopters have developed rapidly, and they have increasingly become the focus of attention.
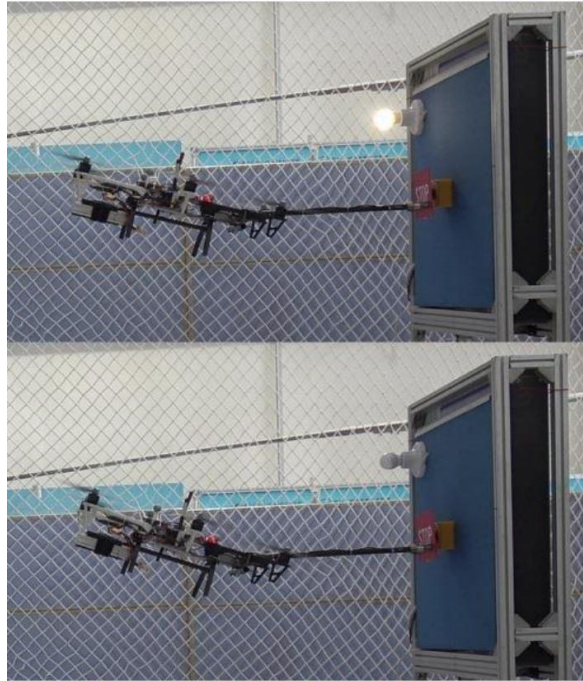

Fig. 3 An aerial manipulator is pressing the emergency switch to turn off the lights [11].

In the lateral or longitudinal motion of helicopter, the motion itself has a certain coupling, which is mainly manifested as the pitching moment caused by blade waving in roll maneuver, the yaw moment caused by rotor rotation, the roll moment caused by pitching maneuver, and the yaw moment caused by the change of tail rotor pull when the forward speed changes. During the flight of the unmanned helicopter, multiple flight modes can be switched, and different modes can be combined at will. The ability of the unmanned helicopter to complete special tasks is comprehensively improved in various complex environments [12]. Therefore, for the flight control system, it is necessary to not only realize the functions of different flight modes but also to optimize the current mode switching mechanism to maintain a high-quality flight state during the switching process [11].

Helicopters also have hovering capabilities. Compared with multi-rotor UAVs, helicopters can be expanded more easily in size and payload capacity. K. Kondak et al. [13] also studied the construction of a helicopter manipulator. Fig. 4 shows the structure of the system. It consists of three main components: a flying platform, a manipulator rigidly mounted on the fuselage, and a sensor system.

Albert Albers et al. [14] added an extra actuator to generate physical contact force while maintaining the level of the drone and proposed a control structure based on ultrasonic distance sensors and CMOS cameras. This system can be applied in high altitudes—physical tasks such as cleaning windows or walls and rescue or maintenance.

Fig. 4. First experimental platform for aerial manipulation with a 7DoF industrial manipulator based on a main-tail-rotor helicopter [13].

2.3.   Novel Aerial Platforms

Researchers have modified existing platforms and continuously developed new aerial platforms. C. C. Kessens et al. [15] considered the limitations of airborne vacuum pumps and put forward the challenge of using suction for multi-purpose aerial grasping. Based on their team's self-sealing suction cup technology, they developed a new aerial platform technology.

C. E. Doyle et al. [16] tried to study a landing mechanism to expand the number of surfaces on which the rotorcraft can land. Under the influence of a kind of bird, they proposed a design that can perch various surfaces, as shown in Fig. 5.

Fig. 5 Quadrotor perching on a cylindrical railing. The grip is actuated by the weight of the quadrotor [16].

3. Manipulating Device

The autonomous grasping, manipulation, and transportation of objects is a basic field of robotics research, which is very important for applications that require robots to interact and influence changes in the environment. With the latest developments in related technologies and commercial micro-aircraft, autonomous grasping, maneuvering, and transportation problems are developing from theory and experiment to aviation.

In order to achieve aerial gripping of various objects, different operating principles have been developed in recent years, including suction grippers, interlock grippers, or magnetic grippers. The most common designs are mechanical fingers or claws because they are easy to manufacture, sturdy and durable, and can handle objects independently of materials and shapes. However, these grabbers require precise positioning or underdrive and flexible design of the drone in order to be able to grab objects reliably.

People divide manipulating devices into three categories: grippers, manipulators, and cables. Based on different scenarios, they are different mechanically as well as in modeling and control.

3.1. Griper

The gripper control system is designed to control the gripper through three modes. The first is to control the opening and closing of the gripper by a switch so that the clamping jaws can clamp the object by applying the maximum force or fully open to release the object. The second mode allows the pilot to control the amount of force the gripper exerts on the object. This function controls each gripper individually to ensure that the overall pressure applied is uniform. The third mode is to use sensors applied to the pilot's forearm to control the claws, thereby mimicking the operation of the pilot's hand. This mode also controls the amount of force applied by each gripper.

This kind of operating device has three advantages: (1) easy to manufacture, (2) convenient to model and control, and (3) relatively cheap. The typical drone robot gripper is the Amazon Prime Air drone, which is used to grab parcels [17]. The design of the drone gripper is designed according to its application. A gripper is installed on the bottom of the aircraft to hold the payload. Michael N et al. [18] designed a hand claw, which drives four hooks into a plane through a servo motor to penetrate the surface of the object.

The mantis claw was designed by Ben Kardoosh [19], a British mechanical engineering graduate. The claw does not require any external power source to work. It consists of five articulated metal claws, which automatically open when they touch the surface of the object. Gather again when the drone returns to altitude. The disadvantage of this design is that the mantis claw is limited to the types of objects it can grasp because this mechanism requires the grabber to grab objects from its bottom, so it cannot grab objects that are level with the ground including boxes. The design of the mantis claw makes it very lightweight, while still having a strong grip, as shown in Fig. 6.

Fig. 6. Mantis Claw Grabbing Objects [19].

Markus Lieret et al. [20] proposed a lightweight, low-cost, self-diagnosing electromechanical gripper suitable for autonomous drones. The gripper provides an energy-saving design and an integrated measurement system that can detect whether the grip is successful or not.

Kiran Setty et al. [21] designed a new type of gripper. Compared with the traditional drone gripper, this gripper can use a drone to grab objects with complex shapes.

Na Zhao et al. [22] present the development of a novel deformable quad-rotor enabled aerial gripper. Two case experiments were carried out on the new aerial gripper. All the results prove the excellent performance of the deformable quadrotor air gripper. That is, it has the advantages of both flight maneuverability and grasping ability when performing tasks.

T Toda et al. [23] develop an angular gripper to realize aerial torsional manipulation, which is mounted on the quad tilt-rotor UAV, and realized the use of quad-rotor drones to remove light bulbs.

As mentioned above, due to its mechanical structure, the gripper has the following shortcomings: (1) limited working space and (2) limited mass and volume grasping capabilities.

3.2. Manipulator

The manipulator is mainly composed of two parts: one or more multi-degree-of-freedom arms connected to the drone's fuselage and clamps with different types of sensors. Generally speaking, the arm and gripper are driven by servo motors. The manipulator expands the working space and is a better choice for performing more complex tasks.

Suseong Kim et al. [24] used two aerial manipulators with multi-rotor and multi-degree-of-freedom manipulators to manipulate the posture of rod-shaped objects. It can be shown in Fig. 7.
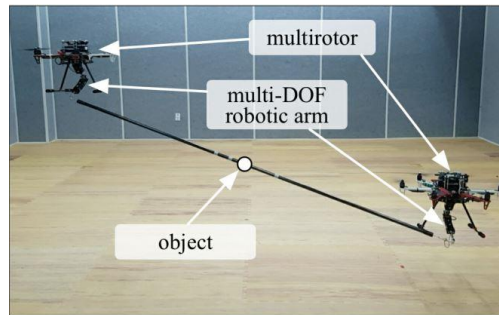

Fig. 7. Two aerial manipulators are manipulating a rod collaboratively [24].

Liu Chao et al. [25] proposed a new type of manipulator for aircraft to complete grasping and maneuvering tasks. The goal is to design a low-cost, relatively light but strong manipulator and propose a new design based on a spiral zipper and tether actuator.

CD Bellicoso et al. [26] proposed a small UAV equipped with an active light manipulator that can apply force on the side of the aircraft. The air system as a whole is customized for contact tasks. In this case, the force transmission of the end effector is the result of the joint action of the active manipulator and the aircraft pitching motion.

The research team of Seoul National University [27] developed an origami-style robotic arm, which is foldable, self-assembled, and has high rigidity.

Ibrahim Abuzayed et al. [28] proposed a lightweight aerial manipulator for quadrotors. The proposed design can correct the CoG drift that may be caused by the movement of the manipulator or the influence of the object.

Karen Bodie et al. [29] proposed a new type of aerial manipulator, including an omnidirectional tilt-rotor flying base equipped with a 3-degree-of-freedom parallel manipulator. It is shown in Fig. 8.

Fig. 8. Omnidirectional delta-based parallel aerial manipulator [29].

The shortcomings of the manipulator can be summarized as follows: (1) complex mechatronics system, (2) heavyweight, (3) difficult to control, (4) severe coupling interference with UAV.

3.3. Cable

Quadrotors are widely used in air transportation missions due to their vertical take-off and landing capabilities and high agility. For quadrotors, one way to carry the payload is to use grippers. However, the use of grippers will slow down the response because the rigidly attached payload on the quad-rotor body will increase the inertia of the system. Therefore, in order to maintain the agility of the quad-rotor system and make the connection between the quad-rotor and the payload more flexible, a method of attaching the payload to the quad-rotor using a cable has been proposed.

More and more people are interested in using multi-rotor platforms to carry suspended loads, which has significant advantages in the fields of cargo transportation, sensor deployment, fire protection, and construction. In this regard, two methods are usually considered. The first is to install grippers or a sufficiently large cargo compartment on the drone, which leads to an increase in takeoff quality, complexity, and cost. As far as aircraft performance is concerned, flight endurance and range will be shortened, and attitude dynamics will be affected by reduced agility. The second method is to transport the suspension load, which relatively maintains the performance of the aircraft and the simplicity of the system, but it introduces additional non-driving degrees of freedom related to the rocking motion [30].

The use of cables to control helicopters is widely used in many fields. Logging companies use helicopters to transport logs and equipment from areas inaccessible to trucks, and power companies use them to transport and assemble wires in remote areas. When the target is in a narrow area or a chaotic environment, it is difficult for a multi-rotor UAV to approach the target and manipulate it directly near the target. For safety, it is important to maintain a safe distance from these targets.

Quad-rotor aircraft with suspended cable payloads have been used for water sampling [31]. Nicotra et al. [32] developed a nested saturation control method for quadrotors to transport suspension cable payloads. Li Zhen et al. [33] proposed a variable aviation streamer system. The length of the driven cable can change the size of the entire system. This means that it is possible to travel through constrained environments or limited spaces.

Ti Chen et al. [34] studied the development of a new type of quad-rotor air transportation system that can carry payloads through four cables.

In summary, when paying attention to control issues during manipulation, a cable or tether is the most suitable. From the mechanical point of view, the gripper is easier to implement than the manipulator. Table 2 compares the controls [35].

Table 2. Compared Control

Manipulating device	Cost	Difficulty	Available range	Stability	Application trend
Gripper	Low	Low	Low	High	Decrease
Manipulator	High	High	High	Middle	Rapidly increase
Cable	Low	Suitable	Middle	Middle	Slowly decrease

4. Modeling and Control of Aerial Manipulator

The aerial manipulator incorporates a number of cutting-edge technologies, the core of which is a flight control technology. After the continuous efforts of a large number of scholars, various control methods have been proposed, including PID control [36], LQR control [37], Impedance control [38][39], backstepping control [40], Model predictive control [41] and so on.

The main difficulty in aerial control is modeling and control. There are currently two modeling methods for aerial manipulators: the first is the independent modeling method, which divides the system into two independent parts, and treats the aircraft and the manipulator as two independent systems without considering the dynamics coupling between them. This method regards the coupling effect as the external interference of the system, and two controllers need to be designed to control the aircraft and the robotic arm. The second is the overall modeling method, which regards the aircraft and the robotic arm as a whole system, considers the coupling between them, and regards it as an internal factor, and designing a controller that can stabilize the aircraft and the robotic arm at the same time.

Rotor-wing flying robot system has the characteristics of multi-input and multi-output, nonlinearity, strong coupling, and under-driving. The coupling between various states is extremely complicated. Therefore, the modeling and control of flying manipulators have become a hot and difficult point of current research. There are the Newton-Euler method and Euler-Lagrange method in dynamic modeling [42]. Two methods are introduced below.

In the recursive Newton-Euler formula, the quadcopter and the manipulator are considered to be two different subsystems that interact on the manipulator base frame. The kinematics equation of a quadcopter equipped with a manipulator is given by the following formula:

$$\begin{bmatrix} M & O_3 \\ O_3 & I \end{bmatrix} \begin{bmatrix} \ddot{p}_v \\ \dot{\omega}_v \end{bmatrix} + \begin{bmatrix} O_3 \\ \omega_V \times (I\omega_V) \end{bmatrix} = \begin{bmatrix} T_q - ge_3^T \\ Q_q + D_q \end{bmatrix} + \begin{bmatrix} f \\ n \end{bmatrix} \tag{1}$$

Where M and I are the mass and inertia matrices of the system. Also, T_q is the thrust force generated by 4 rotors, Q_q is the vector of input torques and, D_q is the rotor-induced drag. Additionally, g is the gravity acceleration, and, $e_3 = [0 \quad 0 \quad 1]^T$, finally f and n are the forces and torques exerted by the manipulator on the quadcopter.

In the Euler-Lagrange method, the equation of motion of the system satisfies

$$\frac{d}{dx}\left(\frac{\partial L}{\partial \dot{\xi}_i}\right) - \frac{\partial L}{\partial \xi_i} = u_i \qquad i = 1, 2, ..., 6 + n_m, \tag{2}$$

Where $L = K - U$ is the Lagrangian, K and U are, respectively, the system total kinetic energy and potential energy, and u is the generalized force vector. Having computed the total kinetic and potential energy, the combined system dynamics can be written as:

$$B(\xi)\ddot{\xi} + C(\xi, \dot{\xi})\dot{\xi} + g(\xi) = u \tag{3}$$

with a generic element of C being given by Christoffel symbols of the first type：

$$C_{ij} = \sum_{K=1}^{6+n_m} \frac{1}{2}\left(\frac{\partial B_{ij}}{\partial \xi_K} + \frac{\partial B_{ik}}{\partial \xi_j} - \frac{\partial B_{jk}}{\partial \xi_i}\right)\dot{\xi}_k \tag{4}$$

And $g(\xi) = \left(\frac{\partial U}{\partial \xi}\right)^T$. The above derivation presents a unified dynamic model of UAM and can be conveniently used for control design purposes.

4.1. Independent modeling and control

For independent modeling, the robotic arm will act as an external disturbance to the aircraft. Regardless of whether there is a manipulator, the inner loop attitude control and the outer loop position are required. When the manipulator is added to the aircraft, the attitude control must compensate for the movement of the manipulator or any reaction torque.

M Fanni et al. [43] used the Newton-Euler iterative algorithm to calculate the force/moment of the manipulator on the flying manipulator and based on this, designed a DOB-based controller to control the flying manipulator. Ma Zhao et al. [44] designed a robust flight controller against internal and external disturbances based on the DOB interference observer based on the UAV cascade PID airborne. It has good robustness when there are three kinds of interferences: manipulator motion, end load change, and external crosswind.

Zhang Guangyu et al. [45] regarded the attached manipulator as the disturbance of the UAV. In the dynamic model, the disturbance is affected by the variable inertia parameters of the manipulator system. Based on the proposed dynamics model, a robust $H\infty$ controller for interference compensation is designed to stabilize the flight of the UAV when the manipulator is running. In May of the same year, Zhang Guangyu et al. [46] designed acceleration feedback enhanced robustness. The controller is based on the UAV's layered inner and outer loop control structure, which can effectively suppress strong wind interference and make the aerial manipulator hover stably and have sufficient accuracy.

Ding Yadong et al. [47] proposed an active fault-tolerant control method for a flying manipulator based on a non-singular terminal sliding mode and an extended state observer. Considering actuator failure and modeling error, combined with the adaptive law of actuator failure, its performance is better than traditional fault-tolerant control methods. AE Jimenez-Cano et al. [48] gave a detailed model of the entire system and an aerial platform control method considering arm movement. It proposed a model-based variable Parameter Integral Backstepping controller.

Sandesh Thapa et al. [49] introduce a decentralized adaptive force control algorithm with a consensus algorithm based on connected graphs to transport a load. Its controller ensures that all quadrotor asymptotically converges to a constant reference speed. It also ensures that all forces applied to the payload converge to the desired set point.

Qi Jing et al. [50] proposed a fuzzy synovial attitude control method based on disturbance observers. The extended state observer was used to estimate and compensate for the disturbance caused by the manipulator motion. At the same time, a full feedforward coefficient adaptive attitude control method based on disturbance observer was proposed, which effectively improved the response speed and robustness of the traditional weight coefficient adaptive algorithm.

Alejandro Suarez et al. [51] proposed an aerial maneuvering robot with a rolling base, which can land and move along the pipeline without wasting the energy in the propeller during the inspection. The proposed robot overcomes the limitations of operating time and positioning accuracy in applying flying robots to industrial inspection and maintenance tasks. Use an algorithm based on Hybrid RRT* (Rapid Exploration Random Tree) to plan the path of multi-rotor and rolling platforms, which minimizes energy consumption.

4.2. Overall modeling and control

For the overall modeling, consider the coupling effect of the robotic arm to the aircraft. The state-space of the dynamic model established by this method includes the position, attitude, and joint angle of the robotic arm of the rotor drone and the state of the rotor drone and the robotic arm. There is a complex nonlinear coupling between the quantities. Eliminate the influence of coupling through robust control or disturbance compensation. Dynamic modeling mostly uses Euler-Lagrange equations. Therefore, after considering the influence of gravity, the Euler-Lagrange equation can be used to model the rigid body dynamics of the flying manipulator.

Liu Yunping et al. [52] designed an exponential approach rate controller based on the synovial PID control method. Compared with the traditional PID control method, this method has better robustness. He Wei et al. [53] designed a two-degree-of-freedom flying manipulator system, modeled the system as a whole, constructed a complete dynamic model of the system

using the Euler-Lagrangian method, and designed the outer ring subsystem. A sliding membrane controller is used, and a PID controller is designed in the inner ring.

Liu Yanchen et al. [54] proposed a decoupling method that uses adaptive/robust technology and reinforcement learning methods to track and control a quadrotor with robotic arm position control. A reinforcement learning method is proposed to control the robotic arm to ensure that the quad-rotor dynamics are minimally affected while following the required trajectory. Through the design of the nominal input, the proposed adaptive algorithm is used to cope with the dynamic uncertainty from the quadrotor, manipulator, and payload.

Vincenzo Lippiello et al. [55] proposed three new image-based visual impedance control laws that enable dual-arm drones equipped with cameras and force/torque sensors to interact physically. Martí-Saumell, Josep et al. [56] proposed a full methodology to control UAMs based on full-body, torque-level, model predictive control. This methodology has been imported from the humanoids and legged robots' community and adapted to the UAM. Develop and compare three different MPC controllers: Weighted MPC, Rail MPC, and Carrot MPC, which differ on the structure of their OCPs and on how these are updated at every time step. To validate the proposed framework, they present a wide variety of simulated case studies.

Seyyed AliEmami et al. [57] proposes a new aviation maneuvering control method based on multi-level model predictive control (MPC) to ensure the closed-loop stability that satisfies the operating constraints in the presence of model uncertainty and external interference. First, the Euler-Lagrangian method is used to establish a detailed nonlinear model of a general aviation manipulator, which is composed of a four-rotor and a 3-degree-of-freedom manipulator. On this basis, a model predictive control method based on a multi-stage disturbance observer is proposed. Under the MPC framework, a new multi-step optimization process can be used to simultaneously complete aerial capture and trajectory tracking tasks.

Hossein Bonyan Khamseh et al. [58] discuss the modeling, control, and state estimation of a maneuvering unmanned aerial vehicle (UAV) composed of a quadcopter and a two-degree-of-freedom manipulator. First, the Euler-Lagrangian method is used to model the coupled dynamics of the quadcopter and its manipulator. After linearizing the obtained model, a linear quadratic regulator was designed to realize the simultaneous control of the quadcopter and the robotic arm. Finally, the UKF-based algorithm is used to estimate the state of the system.

Fengyu Quan et al. [59] combine software and hardware models to develop a modular simulation platform. The platform is developed and integrated with online perception, path planning, visual servo controller, and Pixhawk-based aerial control flight controller module, allowing users to test the complete autonomous grasping process. And a new aerial control framework is proposed to realize autonomous remote capture in clutter dynamic scenes. This method only relies on airborne sensors, does not require an external positioning system, and considers the dynamic obstacles that exist on the pre-planned path.

Min Jun Kim et al. [60] linearized the rotor UAV angular velocity and joint angular velocity in the manipulator end dynamics by using the feedback linearization method, and then designed the regulator with stable characteristics by using the controller design method of a linear cascade control system, In the simulation experiment of the system composed of unmanned helicopter and 7-DOF manipulator, the adjustment of external disturbance in any state direction is realized.

Dimitris Chaikalis et al. [61] deduced the dynamic equation of the UAM system and designed the controller based on feedback linearization and adaptive nonlinear backstepping control. Simulation studies under various operating conditions show the effectiveness of the design.

Aiming at the defects of traditional image-based and position-based visual servoing and the system's own under-drive, Jing tao Sun et al. [62] established a kinematic model and proposed dynamic joint modeling based on the principle of force balance, and passed Euclidean The

homography matrix decomposition designs a hybrid visual servo control method for the rotor flight manipulator system, which controls the translation in the image space and the Cartesian space to control the rotation, which reduces the mutual influence between the translation and the rotation to achieve the decoupling effect, and improves the system performance. The anti-disturbance performance and global stability of non-structural factors. The system robustness and algorithm superiority are verified through simulation and experiment.

Compared with the overall modeling and independent modeling, the overall modeling model is more accurate and is conducive to the design of a unified controller to ensure the overall motion performance of the system, but there are also many shortcomings, such as overall modeling. The resulting model structure is more complex. When the manipulator is operating, the model of the coupling item is established, and the real system will produce certain errors, and the accuracy will be reduced, which will greatly affect the performance of the control algorithm of the system. In contrast, the independent modeling method simplifies modeling and control, and the controller design is simpler by suppressing the disturbance caused by dynamic coupling.

In most cases, a holistic approach is used to control the aerial manipulator group. The holistic approach requires all status information of all subsystems in order to send appropriate commands to each air system. All information must be passed back and forth, which adds extra delay to the drone's controller. In addition, every new UAM that will help achieve the goals of the system will increase the communication burden, making the system unable to be upgraded. However, in the independent approach, each controller of the drone uses only its state vector and the information collected by its sensors [63]. Table 3 summarizes the independent modeling and overall modeling of the aerial manipulator.

Table 3. Review Result

Number	Research institute	Control model	Control Method	Article Source
1	Egypt-Japan University of Science and Technology [43]	Independent modeling	Robust Control	IEEE/ASME Transaction on Mechatronics
2	Shanghai Jiao Tong University [44]	Independent modeling	Robust Control	Machine Design and Research
3	Chinese Academy of Sciences [45]	Independent modeling	Robust Control	IEEE Transactions on Industrial Electronics
4	Chinese Academy of Sciences [46]	Independent modeling	Robust Control	Applied Sciences
5	Nanjing University of Aeronautics and Astronautics [47]	Independent modeling	Fault-tolerant control	Journal of Central South University
6	Universidad de Sevilla [48]	Independent modeling	Variable Parameter Integral Backstepping Control	Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering
7	Sandesh Thapa Oklahoma State University [49]	Independent modeling	Adaptive Control	Journal of Intelligent & Robotic Systems
8	Southwest University of Science and Technology [50]	Independent modeling	Adaptive Control	thesis
9	University of Seville [51]	Independent modeling	PID/RRT*	IEEE Access

Number	Research institute	Control model	Control Method	Article Source
10	The Nanjing University of Information Science and Technology [52]	Overall modeling	Sliding Mode PID Control	Journal of Nanjing University of Science And Technology
11	Institute of Robotics & Automatic Information System [53]	Overall modeling	Sliding Mode Control/PID Control	Acta Aeronautica ET Astronautica Sinica
12	National Cheng Kung University [54]	Overall modeling	Adaptive/Robust Control	IEEE Transactions on Cybernetics
13	University of Naples Federico II [55]	Overall modeling	Visual-Impedance Control	IEEE Robotics and Automation Letters
14	Institut de Robòtica i Informàtica industrial [56]	Overall modeling	Non-linear Model Predictive Control	arXiv.org
15	Sharif University of Technology [57]	Overall modeling	Multi-Stage Model Predictive Control	Aerospace Science and Technology
16	Ryerson University [58]	Overall modeling	LQR Control	Unmanned Systems
17	Harbin Institute of Technology [59]	Overall modeling	Cascade PID Control	arXiv.org
18	German Aerospace Center (DLR) [60]	Overall modeling	Cascade Control	IEEE Robotics and Automation Letters
19	New York University Abu Dhabi [61]	Overall modeling	Adaptive Control	2020 International Conference on Unmanned Aircraft Systems (ICUAS)
20	Hunan University [62]	Overall modeling	Visual Servo Control	Control Theory & Applications

5. Conclusion

The flying manipulator system is the current research hotspot in the field of flying robots. This article introduces the types of aerial platforms and control devices, mainly focusing on the modeling and control problems of flying manipulators at home and abroad. A prominent feature of the aerial manipulator is interference, usually not negligible. Unlike ground robots, aerial robots move in the air. This makes the disturbances caused by the aerodynamics acting on the aerial manipulators time-varying and difficult to model and measure. The controller of this system should be able to respond to unknown disturbances quickly. Therefore, it is a significant problem to design an air manipulator controller with fast dynamics and considering disturbance. Generally speaking, the research of air manipulators is still in the primary stage, and many problems such as coupling effect, flight control, and path planning need to be further studied.

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