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Survey on Aerial Manipulator: System, Modeling, and Control††

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SUMMARY
The aerial manipulator is a special and new type of flying robot composed of a rotorcraft unmanned aerial vehicle (UAV) and a/several manipulator/s. It has gained a lot of attention since its initial appearance in 2010. This is mainly because it enables traditional UAVs to conduct versatile manipulating tasks from air, considerably enriching their applications. In this survey, a complete and systematic review of related research on this topic is conducted. First, various types of structure designs of aerial manipulators are listed out. Subsequently, the modeling and control methods are introduced in detail from the perspective of two types of typical application cases: free-flight and motion-restricted operations. Finally, challenges for future research are presented.

KEYWORDS: Aerial manipulator; Manipulation; UAV; Gripper.

1. Introduction

Rotorcraft unmanned aerial vehicles (RUAVs) are attractive robotic platforms because of their low cost, simplicity of use, and high maneuverability. Thus, many researchers have focused on this field, and fruitful results have emerged during the past decades. Currently, RUAVs find wide application in aerial photography,[1] plant protection,[2] precision farming,[3] disaster assistance,[4] reconnaissance,[5] military support,[6] and so on.

All UAVs are some type of simulation of the flight ability of birds. However, birds are the most diverse and largest group of extant tetrapods, not only because of their wings but also because of their legs. As shown in Fig. 1, their diverse modes of locomotion—walking, running, hopping, flying, and swimming—have enabled birds to colonize almost all the environments on Earth.[7] Unfortunately, most of the current applications of UAVs are of perceptional tasks or at the most, simple operational tasks by equipped typical payload, such as pesticide spraying.

Extensive research has gone into space, ground, and underwater robots, and they have been equipped with robotic arms showing flexible manipulation capacity. This has been extensively accepted and gradually applied in many realities. Most recently, a similar concept, called aerial

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Fig. 1. Birds in nature. (a) Predation, (b) Perching, (c) Grasping.

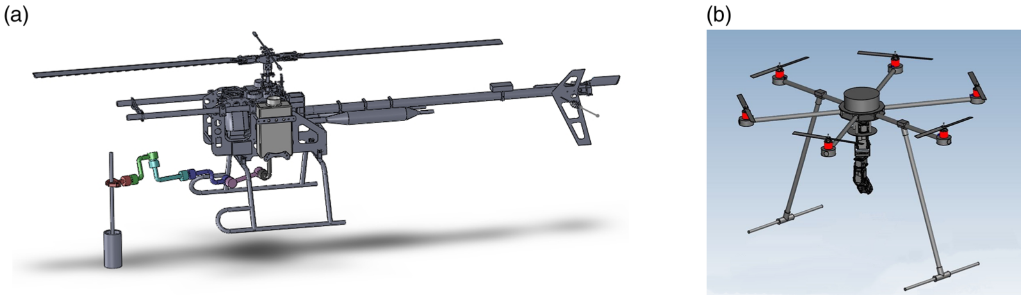

Fig. 2. Aerial manipulation examples. (a) Unmanned helicopter aerial manipulator (Yale University,[8] DLR,[9]) (b) Multirotor aerial manipulator (University of Pennsylvania,[10] Drexel University,[11]).

manipulator (AM), has been introduced to the field of flying robots. It is composed of a traditional flying robot and manipulator(s), as shown in Fig. 2. The UAV provides a stable aerial platform in 3-dimensional (3D) space for movement or hovering. The manipulation mechanism (which could be grippers or robotic arms) enables the ability to conduct active operations in air.

The AM system has attracted great research enthusiasm in the field of mobile robotics. Numerous research groups have made positive contributions to AM development. Universities in America show interest in grippers (usually installed beneath the UAV fuselage) to perform grasping and perching tasks. The research institutions and universities in Europe are more interested in robotic arms to conduct various complex manipulating missions (pick-and-place, peg-in-hole, contact inspection, etc.). Other groups have also done some research on AM based on both gripper and manipulator. For clear understanding, Table I is summarized to present the worldwide research groups and their achievements.

Some top academic conferences and forums have conducted pertinent workshops to share and discuss the progress of research in aerial manipulation, such as RSS (Robotics: Science and Systems),[12] ERF (European Robotics Forum),[13] ICRA (International Conference on Robotics and Automation),[14–18] and IROS (IEEE/RSJ International Conference on Intelligent Robots and Systems).[19] Among them, ERF and ICRA presented new topics every year from 2014 to 2018. Driven by potential applications of AM, some projects, such as AEROARMS,[20] ARCRS,[21] AIRobots,[22] AEROBI,[23] AEROWORKS,[24] HYFLIERS,[25] and SEIDROB, are funded to encourage further research and development.[26]

The emerging AM research results can be grouped into two major categories: free-flight operation and motion-restricted operation. Free-flight operation is when the AM systems conduct tasks in free-flight mode. Here, the contact force appears for a very small time period, and the force value is usually negligible in interaction process.[27–31] Motion-restricted operation is when the AM system is required to physically interact with the environment or object for a sustained time period with a fixed and desired force, and the UAV motion is usually restricted leading to the loss of some degrees of freedom (DOFs).[32–37]

The introduction of manipulation mechanism and requirement of high operational capability make AM research challenging, which mainly focuses on system modeling and control. In addition to the same characteristics as UAV systems (nonlinear, strong-coupling, under-actuated, etc.), an AM is a multi-rigid body, interacting with the external environment, and difficult in parameter identification and estimation, making it more complicated than regular UAV dynamics. Some original

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Table I. AM research group and main achievement.

No.	Research group	AM platform	Parameter and performance	Modeling approach	Control approach	Implementation	Main manipulation task
1	Yale University[8,45–49]	Helicopter, Compliant Gripper	UAV 4.3 kg, Load 1 kg	Separated	PID	Outdoor flight experiment	Grasp a static unstructured object in hover flight
2	University of Pennsylvania[10,69,113,141–144]	Quadrotor, Gripper	UAV 388 g, Gripper 478 g, Payload 77 g	Overall	PID, Visual servoing	Indoor flight experiment (MOCAP)	Grasp, perch, pick up, and transport payloads, Construction with quadrotor teams
3	Drexel University[11,35,39,44,72,86,93,101,109]	Quadrotor, Dual 2-DOF arm, Dual 4-DOF arm, Serial chain arm, 6-DOF manipulator	UAV 721.8 g, Gripper 64.6 g, Payload 200 g	Separated	MRAC, Adaptive PID, Visual servoing	Simulation, Indoor flight experiment (MOCAP)	Grasp a static object in near-hover flight, Turn a valve, Peg-in-hole task test
4	Johns Hopkins University[67,75,81]	Coaxial octo-rotor, 2-DOF arm, Quadrotor, Yale Open Hand based gripper	UAV 1.95 kg, Gripper 0.372 kg, Total 2.3 kg	Overall, Separated	Back-stepping control, Feedback linearization and PID, Model-predictive control	Simulation, Indoor flight experiment (MOCAP)	Autonomous perching, Aerial pick-and-place
5	Utah State University[73]	Quadrotor, Gripper	UAV 1.4 kg, Grasp object up to 7.5 cm	Separated	PID	Indoor flight experiment	Grasp a static object under position uncertainty
6	Stanford University[105,106]	Quadrotor, Gripper	UAV 120 g, 1 × 1 cm square adhesive tiles	Separated	Modeling in Motion Genesis	Simulation	Dynamic surface grasping

Table I. (Continued)

No.	Research group	AM platform	Parameter and performance	Modeling approach	Control approach	Implementation	Main manipulation task
7	University of Nebraska-Lincoln[119]	Quadrotor, Gripper	Gripper 1.2 kg System length 540 mm	Separated	Radio control operation	Outdoor flight experiment	Underground sensor installation
8	Purdue University[60,61,128]	Tri-rotor UAV (I-Boom Copter), Push-to-release end-effector, Hexa-rotor, Nonparallel actuation mechanism LVL1	Overall size 60 cm × 70 cm × 29 cm, (One battery) Mass 2.31 kg, Max payload 1.86 kg, Max speed 17 m/s, Flight time 13 min	Separated	Vision-based control, PID	Indoor flight experiment (MOCAP)	Open a door, Physical interaction task
9	Illinois Institute of Technology[76]	Quadrotor, Gripper	Total 550 g	Separated	PID	Indoor flight experiment (Kinect)	Autonomous perch and take-off on a vertical wall
10	University of Nevada[167]	Quadrotor, 3-DOF arm,	UAV 2400 g, Arm 327 g	Separated	Passive control	Simulation	Transition from free-flight to contact mode
11	German Aerospace Center (DLR)[9,50–53]	Helicopter, 7-DOF industrial arm	UAV 37.6 kg, LWR arm 14 kg	Separated, Overall	PID, Impedance control, Passive compliance control	Simulation, Outdoor flight experiment	Grasp a static pole and pull out of the fixing, Grasp a static object in hover flight
12	Max Planck Institute for Biological Cybernetics[27,153,165]	Quadrotor, Gripper, 1-DOF arm	UAV 1.0 kg, Arm 0.36 kg	Separated	Trajectory optimization, Differentially flat system control	Simulation, Indoor flight experiment (MOCAP)	Grasp a moving target, Pick-and-place operation, Physical interaction task

Table I. (Continued)

13	University of Seville[31, 32, 68, 92, 97–99, 126, 127, 130, 151, 157, 163]	Coaxial octo-rotor, 7-DOF arm, Hexa-rotor, Dual 4-DOF arm	Coaxial octo-rotor UAV 7.3 kg, Arm 1.3 kg Hexarotor UAV 5 kg, Dual arm 1.5 kg	Separated, Overall	PID, Visual servoing, Impedance control	Outdoor flight experiment	Grasp and transport static object, Long-reach manipulation, Contact inspection
14	ETH Zurich[29, 62, 74, 85, 108, 115, 129]	Quadrotor, Magnetic gripper, Tri-tiltRotor UAV, 1-DOF arm, Parallel arm	Painting UAV total 4.2 kg, Arm 140 g; Contact UAV 0.65 kg	Separated, Overall	PID, MPC, PID-Double derivative, PI-Rate-Varying Integrator (RVI)	Indoor flight experiment (MOCAP)	Grasp and transport for both static and moving objects, Forward-pushing, Flight assembled architecture installation, Spray painting on a surface
15	University of Naples Federico II[40, 82, 100, 110, 114, 131, 162]	Quadrotor, 5-DOF arm, Coaxial octo-rotor, Dual 4-DOF arm	UAV payload 0.65 kg, Arm 0.25 kg, Coaxial octo-rotor total mass 8.2 kg	Overall	Image-based visual-impedance control, Hybrid visual servoing	Simulation, Indoor flight experiment (MOCAP)	Interaction with environment, Grasp static object
16	University of Bologna[88, 145]	Ducted-fan UAV, 2-DOF prismatic arm	UAV 1.8 kg, Arm 0.1 kg	Overall	Modified thrust-vector control	Indoor flight experiment	Docking to a surface
17	University of Siena[135, 147]	Quadrotor, 1-DoF arm	UAV 1.0 kg	Separated	Tele-operate	Simulation	Grasp and manipulate objects by swarm
18	University of Cassino and Southern Lazio[78]	Coaxial octo-rotor, 6-DOF arm	UAV total 8.2 kg	Overall	Null Space-based trajectory planning	Indoor flight experiment (MOCAP)	Avoid obstacles when tracking the planned trajectory

Table I. (Continued)

No.	Research group	AM platform	Parameter and performance	Modeling approach	Control approach	Implementation	Main manipulation task
19	University of Basilicata[38, 155]	Coaxial octo-rotor, 6-DOF arm, Quadrotor, 5-DoF arm	UAV 2.0 kg, Arm 99.5 g	Overall	Adaptive hierarchical inner-outer loop control	Simulation	Motion control in the presence of non-idealities and model uncertainties
20	University of Bristol[89, 122]	Quadrotor, 2-DOF arm	UAV 1.9 kg, Payload 0.55 kg	Separated	PID	Indoor flight experiment (MOCAP)	Interaction with a wall
21	University of Toulouse[63–65, 139, 148, 164]	Tilt-hexa-rotor, 1-DoF arm	Tilt-hex rotor total 1.8 kg, OTHex total 2.48 kg, Quadrotor UAV 1.3 kg, Arm 0.268 kg	Overall	Hierarchical control, Decentralized flatness-based control	Indoor flight experiment (MOCAP)	Interaction with environment, Contact force control, Grasp and lift a horizontal bar
22	University of Twente[70, 83, 84, 90, 91, 154, 166]	Quadrotor, Parallel arm, 2-DOF arm, 1-DOF arm	UAV 1.8 kg, Arm 0.1 kg, Contact UAV total 1.8 kg / 1.5 kg	Separated, Overall	Impedance control, PI controller, LQR-optimized control	Indoor flight experiment (MOCAP)	Contact force control with/ without disturbance
23	University of Zagreb[124, 156, 161]	Hexa-rotor, Dual 4-DOF arm	UAV 957.597 g, AB Arm 37 g	Overall	Impedance control	Indoor flight experiment (MOCAP)	Peg-in-hole insertion, Contact force control
24	University of Auckland[33, 102, 116]	Coaxial octo-rotor, 6-DOF arm	Total 10.23 kg, Arm 8.9 kg	Overall	PID	Indoor flight experiment (MOCAP)	Canopy sampling
25	Seoul National University[37, 79, 107, 111, 117, 121, 132–134, 136, 140, 146, 158, 159]	Quadrotor, 2-DOF arm, Hera-rotor, 3-DOF arm	ODAR system total 2.6 kg, Quadrotor UAV 0.9 kg, Arm 0.37 kg	Separated, Overall	Adaptive sliding mode control, Image-based visual servo	Indoor flight experiment (MOCAP)	Grasp a static object in hover flight, Cooperative transport

Table I. (Continued)

26	Ritsumeikan University[104, 152]	Hera-rotor, 2-DOF arm, Gripper	UAV 2.6 kg, Gripper 0.3 kg	Separated	Vision-based control	Outdoor flight experiment	Grasp a bar and fix at an elevated altitude
27	Meijo University[125]	Octo-rotor, 1-DOF arm	Contact UAV total 15.4 kg, Width 1.8 m	Separated	PID	Outdoor flight experiment	Bridge contact inspection
28	Tokyo Institute of Technology[34]	Quadrotor, Airbag manipulator	ADD-Arm total 160g	Separated	Remote control	Indoor flight experiment	Perch and door-open
29	Shenyang Institute of Automation (Chinese Academy of Sciences)[28, 36, 41, 54–59, 80, 149, 150, 160]	Helicopter, Gripper; Hera-rotor, 7-DOF arm, Quadrotor, 1-DOF arm	UAV 12 kg, Gripper 2 kg, Contact UAV total 2.305 kg, Hex-rotor UAV 3 kg, Arm 1.5 kg	Overall, Separated, Closed-loop based modeling	PID, LQR, Feedback linearization and H8, Impedance control	Outdoor flight experiment, Indoor flight experiment (MOCAP)	Grasp a static object in hover flight, Grasp a moving object in mobile flight, Press a switch
30	Beijing University of Aeronautics and Astronautics[94–96]	Quadrotor, Dual 2-DOF arm	UAV 1.251 kg, Arm 0.173 kg	Overall, Separated	TLC, Computer torque control	Simulation	Motion planning in wall-climbing mode
31	Harbin Institute of Technology Shenzhen[112]	Coaxial octocopter, 4-DOF arm	Total 5464 g, Arm 545 g, Gripper 26 g Payload 200g	Separated	PID, NSGA-II trajectory planning	Indoor flight experiment (MOCAP)	Visual grasp a static object in hover flight
32	Beijing Institute of Technology[71, 138]	Dual ducted-fan UAV, 3-DOF arm, Quadrotor, Wasp inspired gripper	Total 5.5 kg, UAV 4.6 kg, Arm 0.9 kg, Payload 2.0 kg	Overall, Separated	PID	Simulation, Indoor flight experiment (MOCAP)	Grasp objects with various shapes
33	Other groups[168–171]	Quadrotor, Hera-rotor Gripper, Multi-DOF arm, etc.	UAV 2.4 kg, NEO hex-rotor UAV 2.853 kg	Overall, Separated	PID, Inner-outer control, etc.	Simulation, Indoor flight experiment (MOCAP)	Comparison of CoM offset, Contact-based Inspection, etc.

effective control algorithms used on UAVs perform poorly when applied to AM systems.[38] Two main approaches, decentralized approach and centralized approach, appear in existing literature to address modeling and control problems in both free-flight and motion-restricted operation research. The first approach regards the AM as two subsystems; the manipulator subsystem impact is treated as dynamics disturbance for UAV subsystem,[39] and the UAV motion also has influence on manipulator kinematics. The second approach considers the AM as a unified system and uses the combined AM system dynamics in analysis and control.[40] Another distinctive approach for modeling and control is the closed-loop UAV model-based method,[36,41] and it particularly studies the contact force control in an interactive scenario.

The main purpose of this article is a survey on AM, including physical system, modeling, and control techniques, to help those interested to completely understand existing AM research. The rest of the article is, thus, organized as follows. In Section 2, the AM system structures and manipulation tasks are summarized. The modeling and control summaries for free-flight operation and motion-restricted operation are separately introduced in Sections 3 and 4. Challenges and future research are analyzed in Section 5. The last presents the conclusions for this article.

2. System Structure and Manipulation Task

AM system structures (including UAV platform and manipulation mechanism) are introduced in this section first, and manipulation tasks are described later.

2.1. UAV platform

A rotorcraft UAV can achieve free and hovering flight in complex 3D space, making it easier to interact with external environment; thus, it is selected as the platform in most of the existing research. The rotorcraft systems (regular and nonregular) used in aerial manipulation are introduced next.

2.1.1. Unmanned helicopter. Unmanned helicopters have many advantages in aerial operation: large takeoff weight to carry one (or several) multi-DOF manipulator(s), long flying duration capability to fulfill time-consuming tasks (oil-powered), and long-distance flight capability without refueling to improve work efficiency (oil-powered).[42] However, helicopters usually have complex mechanisms and complicated aerodynamic characteristics,[43] causing difficulties in controller design. They are difficult to operate due to oscillation effects caused by the main rotor, for example, mechanical resonance in the air and ground resonance. A serial manipulator connected to helicopter fuselage makes the system extremely sensitive to all vibration and resonance effects.[9] In addition, the manipulation tasks can be conducted only beneath the main propeller due to the limited manipulator workspace and larger propeller area.[44] In addition, helicopters generally fly in an outdoor environment and rarely find application indoors. Yale University,[8,45–49] German Aerospace Center (DLR),[9,50–53] and Shenyang Institute of Automation (Chinese Academy of Sciences)[28,54–59] have conducted aerial manipulation research based on helicopter platforms.

2.1.2. Multi-rotor UAV. Multi-rotor UAVs are popular manipulation platforms owing to the mechanical simplicity, easy-to-implement flight controller design, lower vibration, low cost, easy operation, and flying flexibility in indoors and outdoors. Their disadvantages are also evident, such as low payload, limited flight endurance, and low mechanical efficiency (a multi-rotor UAV usually has a larger airframe than a helicopter under the same payload condition.). Nevertheless, a majority of research groups use multi-rotor UAV platforms that are based on regular multi-rotor UAVs (quadrotor, hexarotor, and octo-rotor), as shown in Table I. In addition, other types of multi-rotor aircrafts have also been developed and applied in aerial manipulation, such as tri-rotor,[60,61] tri-tiltrotor,[62] tilt-hexarotor,[63–65] disk-shaped hexa-rotor,[66] coaxial hexa-rotor,[67] coaxial octo-rotor,[68] and cuboid modular quadrotor.[69]

In addition to helicopters and multi-rotor UAVs, other hovering aircrafts, such as ducted-fan UAV[70,71] and hybrid quadrotor-blimp aircraft,[72] are feasible options in aerial manipulation.

Regular helicopter and quadrotor UAVs have been shown in Fig. 2, and these aforementioned nonregular UAV systems are presented in Fig. 3.

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Fig. 3. Various UAV platforms for aerial manipulation. (a) Quadrotor, (b) Hexarotor, (c) Ducted-fan UAV, (d) Coaxial octorotor UAV, (e) Tilt-rotor UAV, (f) Mini ducted-fan UAV. Other platforms: Purdue University,[60,61] University of Patras,[62] University of Toulouse,[63–65] University of Denver,[66] Johns Hopkins University,[67] University of Seville,[68] University of Pennsylvania,[69] University of Twente,[70] Beijing Institute of Technology,[71] Drexel University.[72]

2.2. *Manipulation mechanism*

AM systems can conduct different aerial operations, which are mainly determined by their manipulation mechanism. A variety of manipulation structures are designed and installed on UAV platforms, and there are two main categories: gripper and manipulator.

2.2.1. Gripper. A gripper is usually installed under UAV fuselage, and located near the overall system center-of-mass (CoM), to conveniently grasp objects. Due to the light weight, little change of CoM, and no relative motion of grasped objects, grippers have limited impacts on UAV dynamics. A gripper has two main states: grip and release, which can effectively achieve some simple operations, such as grasping,[10,73] transportation,[8,28] assembling,[10,74] and perching.[75–77] However, a gripper generally needs to be specifically designed for a certain purpose to suit different object shapes, surface textures, materials, and weights. In addition, there are some key specific requirements for the gripper

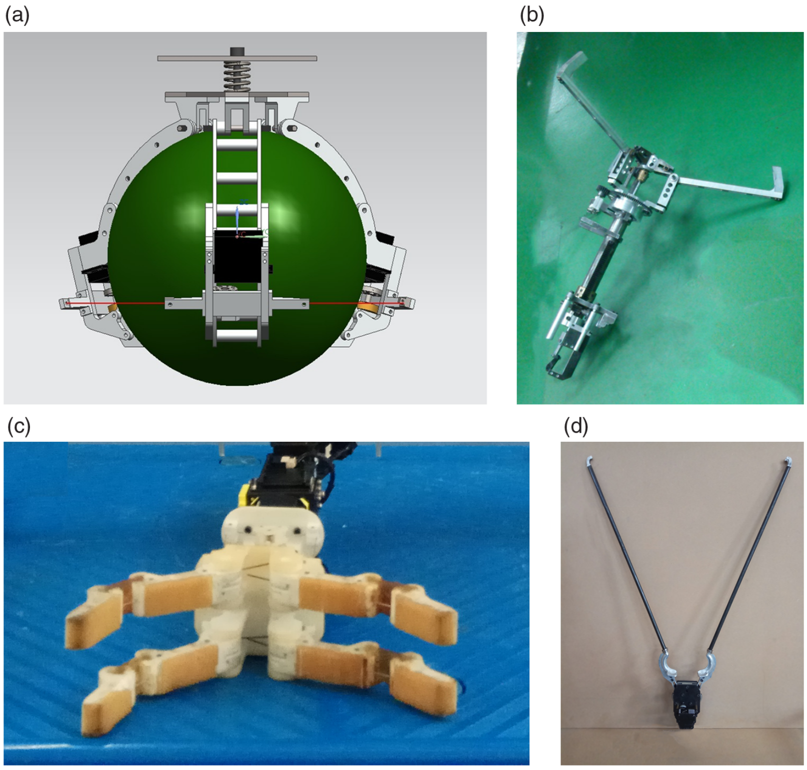

Fig. 4. Gripper examples. (a) Ball gripper, (b) Three-finger gripper, (c) Yale hand, (d) Simple gripper. Other grippers: Yale University,[8] University of Pennsylvania,[10] Utah State University,[73] ETH Zurich,[74] Johns Hopkins University,[75] University of Utah.[77]

in aerial manipulation application,[73] such as light-weight, compliance, minimal actuation, ability to flatten itself, and reliability in installation. Servos are commonly used as gripper driving parts for open/closed position control. Some representative grippers are shown in Fig. 4.

2.2.2. Robotic manipulator. Robotic manipulators are more widely used in aerial manipulation and have many advantages than simple grippers. The multi-DOFs contribute to expanding operation space, acquiring versatile operating skills, and increasing mission adaptability. Thus, it can fulfill some complicated tasks, such as forest canopy sampling,[33] opening/closing a door,[34] and turning a valve up/down.[35] End-effectors also have a variety of designs to meet different requirements of both instantaneous and long-time continuous contact operations. Most of AM research is based on multi-DOF manipulators, and various categories emerge. Some classifications and representative airborne manipulators are presented here:

- Industrial or ordinary: German Aerospace Center (DLR) uses an LWR KUKA industrial manipulator as depicted in Fig. 2(b).[51] Others are mostly servo-driven ordinary robotic arms.[31,32,68,78–82]
- Parallel or serial structure: University of Twente,[70,83,84] ETH Zurich,[85] Lockheed Martin's Advanced Technology Lab,[86] and University of Malaga[87] use parallel manipulators; others are mostly serial structures.[9,11,31,32,78–82]
- Revolute or prismatic joint: Prismatic joint manipulators are used by University of Bologna,[88] University of the West of England,[89] and University of Twente.[90,91] Other manipulators are with revolute joints.[8–11,31–40,78–82]
- Redundant manipulator: A considerable number of manipulators with multiple DOFs have been developed for aerial operations, as shown in Table I. The DOFs of most aerial manipulators are less than or equal to 6. Some research groups use 7-DOF redundant arms; they are DLR,[51] University of Seville,[68,92] and Shenyang Institute of Automation (Chinese Academy of Sciences).[80] A 9-DOF redundant arm is also used by Drexel University.[93] These redundant manipulators can be found in Figs. 2(b), 3(f), and 5(a).

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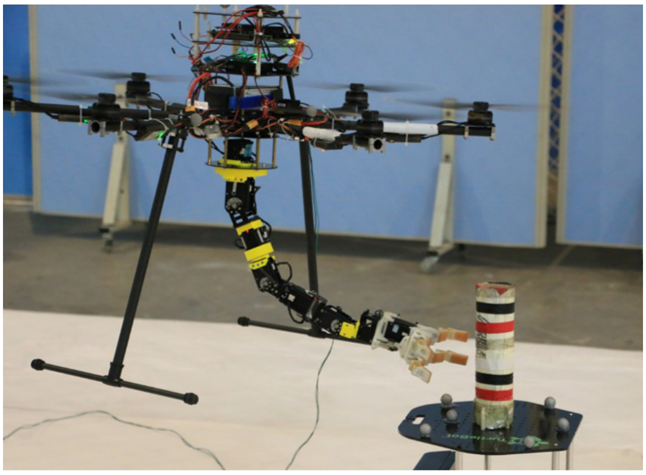

Fig. 5. Free-flight operation example. Shenyang Institute of Automation, Chinese Academy of Sciences,[80] Seoul National University.[107]

- Dual-arm system: Most of aerial manipulation research uses only one manipulator, but dual-arm AM systems are also studied by Drexel University,[11] Beijing University of Aeronautics and Astronautics,[94–96] University of Seville,[97–99] and University of Naples Federico II.[100]

In addition to the aforementioned regular grippers and manipulators, some novel mechanisms are designed for special applications, which can be found in the research of Purdue University,[60,61] Drexel University,[101] University of Auckland,[102] Tohoku University,[103] Ritsumeikan University,[104] Stanford University,[105,106] and others.

2.3. *Manipulation task*

Based on these AM systems, a variety of aerial manipulating tasks have been conducted, which can be mainly grouped into two categories: free-flight operation and motion-restricted operation.

2.3.1. Free-flight operation. The free-flight operation is when an AM system conducts tasks in free-flight mode, as depicted in Fig. 5. The contact force appears for a very small duration, and the force value is usually negligible in interaction process. Most of free-flight operations are concentrated on grasping[27,45–47,79–81] and transporting.[28,39,69,73,75] Other types of operations are delivering,[29] perching,[30,76,77] assembling,[31,74] pick-and-place,[81,107] and so on. These aerial manipulating tasks generally demand accurate position information; therefore, they are often performed in motion capture system (e.g., VICON and OptiTrack).[39,41,63,71,108] Visual method is usually used for recognition and location of target and motion guidance.[109–114]

2.3.2. Motion-restricted operation. The motion-restricted operation means that an AM system physically interacts with the environment or object for a continuous time period with a fixed and desired force, as depicted in Fig. 6. This may result in the loss of some DOFs as the UAV motion is restricted by the external environment. The motion-restricted operations can be further divided into two types. The first type considers the contact force as a system indicator, and the force needs to be maintained only within a certain threshold range. The related research is as follows: turning a valve,[11] structure inspection,[32,115] canopy sampling,[33,116] opening a drawer,[117] collision-recovery control,[118] underground sensor installation,[119] and other aerial applications.[89,120–123] The second type sets the force as one of control goals and tries to maintain an accurate desired contact force (fixed or dynamic force). These operations are pressing a switch,[36] peg-in-hole operation,[37,124] bridge inspection,[125,126] and other contact-based missions.[41,63,83,85,89,127–130]

In addition, the cooperative aerial transportation of AM systems has also been developed to carry a heavier or bulkier object, which shows greater capacity than that of a single AM. Two multi-DOF AMs are usually used to fulfill cooperative tasks, and studied by University of Naples Federico II,[131] Seoul National University,[132,133] and University of Zurich.[134] Multiple (more than

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Fig. 6. Motion-restricted operation example. Shenyang Institute of Automation, Chinese Academy of Sciences,[36] University of Seville.[127]

two) AMs cooperative transportation research is conducted in some other groups.[135–138] However, an AM is also expected to cooperate with ground manipulator, which is called MAGMaS (Multiple Aerial-Ground Manipulator System), and is researched by University of Toulouse[139] and Seoul National University.[140]

Remark 1. The flying platforms for AM research are mainly multi-rotor UAVs. Helicopters account for a small proportion, and other types of UAVs are also available. Multi-rotor aircrafts are widely used because of their low cost and easy operation, but the limited payload and flight time are evident disadvantages. The helicopter's greatest advantages are large payload and long flight time, but in practice the aircraft system is too complicated to be widely applied. Thus, the bulk of AM research still centers on multi-rotor UAVs.

Remark 2. The manipulation mechanisms are of four types: gripper, special structure, manipulator, and manipulator equipped with a gripper. A gripper can only perform grasping or perching task. The specially designed structure usually satisfies a certain operation. These two types are light weight, easy-to-implement, and convenient in control, making it possible to be applied to various UAVs. Strong pertinence of operation object, weak universality, and single function are their problems in application. The manipulators and those equipped with a gripper are able to fulfill many versatile complex missions, but their larger weight limits their wide application in small-scale UAVs. Nevertheless, the general dexterous manipulator (which contains a manipulator and a gripper) will be more popular in future research.

Remark 3. The manipulation tasks can be grouped into several categories: free-flight operation, motion-restricted operation, and cooperative operation. Just like an industrial manipulator, an AM is able to fulfill stacking, polishing, painting, assembling, and even welding tasks. In addition, the AM system essentially imitates a bird (not only its wings but also its legs); thus, bird-inspired tasks are expected to be performed, such as high-speed aerial grasp, perching in dense woodlands, hopping on a branch, pecking a hole like a woodpecker, and walking like a duck.

3. Free-Flight AM Research

A large quantity of research has been conducted to push AM development, as indicated in Table I. Two different categories of aerial manipulation tasks emerge in existing works: free-flight operation and motion-restricted operation, which have been clearly introduced in Section 2.3. Both of them have their own research problems and solutions, and they will be respectively presented in this section and next section.

The free-flight operation is researched earlier, which mainly focuses on modeling and control, and will be, respectively, discussed from decentralized approach and centralized approach in the following sections.

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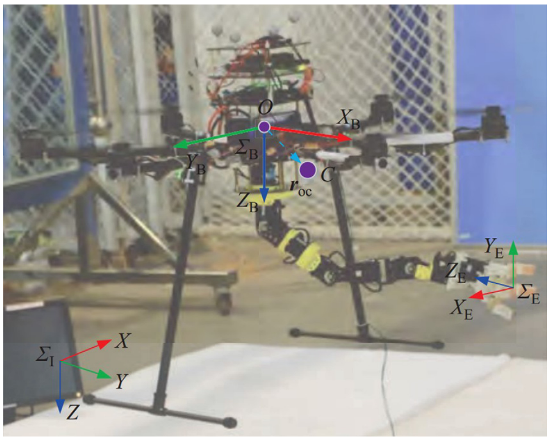

Fig. 7. Frames of AM system based on the separated approach.

3.1. Decentralized approach

3.1.1. Modeling. The decentralized approach regards the AM as two distinct subsystems, wherein the manipulator subsystem impact is treated as dynamics disturbance in UAV modeling process, and the UAV motion also has influence on manipulator kinematics.

Thus, the decentralized UAV dynamics usually has similar forms as that of a regular UAV. Moreover, the coupling impact introduced by manipulator movement is reflected in UAV CoM position and moment of inertia.[8,9,11,31,45,47,60,101,150] On the other hand, the modeling (both kinematics and dynamics) for a sole robotic manipulator can be easily derived by using Denavit–Hartenberg (DH) convention and Newton-Euler method.[35,79,82,98,103,109]

Based on this decentralized analysis idea, the AM coordinate frames are often defined as shown in Fig. 7.[80,160] Σ_I, Σ_B, and Σ_E, respectively, denote the earth-fixed inertial frame, UAV body fixed frame, and manipulator end-effector frame. Point O is the coordinate origin of Σ_B, and it coincides with UAV CoM. Then the UAV platform dynamics can be obtained through Newton-Euler equation, and is shown as follows:

$$\begin{cases} \dot{\boldsymbol{p}}_b = \boldsymbol{v}_b \\ \dot{\boldsymbol{v}}_b = g\boldsymbol{e}_3 - 1/mF\boldsymbol{R}_b\boldsymbol{e}_3 - \\ \qquad \boldsymbol{R}_b(\dot{\boldsymbol{\omega}}_b^b \times \boldsymbol{r}_{OC}^b(\boldsymbol{q}) + \boldsymbol{\omega}_b^b \times (\boldsymbol{\omega}_b^b \times \boldsymbol{r}_{OC}^b(\boldsymbol{q}))) \\ \dot{\boldsymbol{R}}_b = \boldsymbol{R}_b S(\boldsymbol{\omega}_b^b) \\ \dot{\boldsymbol{\omega}}_b^b = \boldsymbol{I}_b^{-1}(\boldsymbol{M} - \boldsymbol{\omega}_b^b \times (\boldsymbol{I}_b\boldsymbol{\omega}_b^b) + \boldsymbol{r}_{OC}^b(\boldsymbol{q}) \times F\boldsymbol{e}_3) \end{cases} \tag{1}$$

where $\boldsymbol{v}_b$ is the UAV velocity with respect to Σ_I, g is gravity acceleration, m is the mass of overall AM system, $\boldsymbol{F}$ is total thrust generated by UAV rotors, $\boldsymbol{q}$ is the manipulator joint vector, $\boldsymbol{r}^b{}_{OC}$ $(\boldsymbol{q})$ is arm CoM offset with respect to Σ_B, and it is a function of $\boldsymbol{q}$. $\boldsymbol{\omega}^b{}_b$ is UAV angle velocity with respect to Σ_B. $S(.)$ indicates the skew symmetric matrix. $\boldsymbol{I}_b$ is AM inertia matrix referenced to O. $\boldsymbol{M}$ is total moments acting on point O with respect to Σ_B.

3.1.2. Control. Because an AM system has been modeled into two subsystems, two separate controllers need to be designed, as the example in Fig. 8. A PID controller is usually applied to a manipulator system to achieve joint motion control.[49,85,87,102] The manipulator trajectory has to be planned to fulfill some manipulation tasks, such as track a desired end-effector trajectory to grasp target objects, and avoid obstacles in aerial manipulating process. Although the UAV platform is a moving base with respect to the manipulator, only the kinematic impact on a robotic arm is considered in aerial manipulation, and the dynamic coupling effects on a manipulator subsystem are usually neglected, which is the characteristic of the decentralized approach.[109,112]

The UAV control has various methods as shown in Table I. General techniques (e.g., disturbance estimation, controller compensation, and predictive control) are necessary to improve system accuracy and robustness.[47,168] Some control algorithms ever used on regular UAVs are being considered

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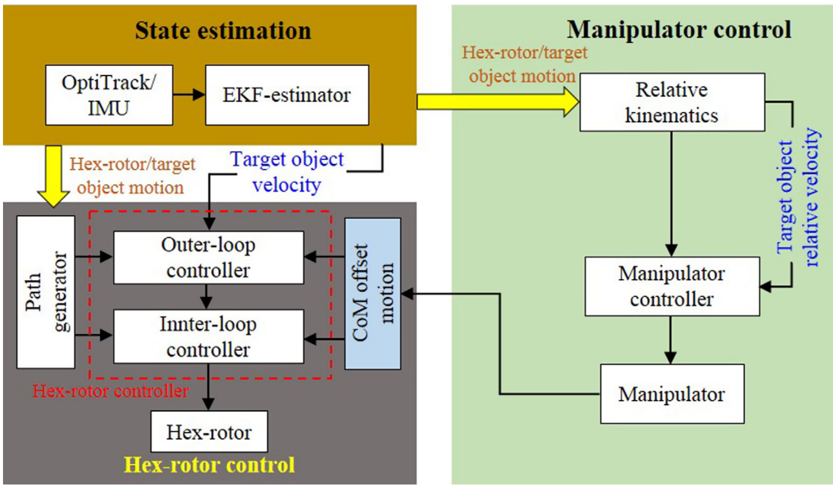

Fig. 8. Control structure of AM system based on decentralized approach.

to be applied to AM systems as well as with some modifications. For system model, due to the introduction of robotic arms, two main problems appear. First, the UAV body dynamics becomes more complicated as indicated in Eq. (1). The movement of manipulators usually changes UAV moment of inertia and CoM position. Second, in addition to propeller aerodynamic force, the counterforce caused by joint motors has impacts on UAV dynamics. For system control in aerial operations, compared with traditional free-flight control, the UAV stability under external disturbance becomes more important. Thus, these disturbances need modeling, measurement, or estimation first, and the impacts on system are eventually weakened by controller design. In addition, the multi-controller method is often applied to realizing the control of different flight modes (free flight, grasping flight, etc.). A variable parameter integral back-stepping (VPIB) control is designed to guarantee system asymptotic stability and has shown robustness to some uncertainties.[31] The dynamic load disturbances introduced by the load mass can be rejected by a helicopter with PID flight control and have been tested by experiments of grasping and retrieval of a variety of objects in hovering flight.[47] Two independent controllers have been developed to address the coupling between manipulator and helicopter.[51] A gain schedule PID is used to stabilize the system while the robot arm moves.[150] A feedforward compensation linear H-inf flight controller is designed to eliminate unsteadiness due to the relative motion between UAV and manipulator.[160] A hybrid adaptive control (a combination of gain scheduling and Lyapunov-based model reference adaptive control) is able to achieve dynamic stability in aerial operating process.[161] The inner-outer-loop control strategy also proves effective efficiency when an AM grasps a moving object from the air.[80,168]

Remark 4. The decentralized approach in free-flight operation research has many advantages. It has a clear modeling method and simple dynamics form, and the coupling effect can be quantified by some indicators (CoM or moment of inertia). Many modified UAV control algorithms can be effectively used to deal with coupling problems resulting from manipulator movement. However, this approach can apply only to slow relative motion between a manipulator and a UAV platform, wherein the velocity of CoM offset, Coriolis force, and centrifugal force are small.

3.2. Centralized approach

3.2.1. Modeling. A UAV owns 6 DOFs in 3D space, and a robotic manipulator usually has n DOFs, which creates an AM system with 6+n DOFs. The centralized modeling approach treats an AM as an ordinary multi-rigid-body system; thus, the AM dynamics can be derived by using either the recursive Newton-Euler or Euler-Lagrange formulations.[173] Although both these methods could lead to an identical motion equation, the Euler-Lagrange formulation is usually used in the centralized research approach as it is better suited for dynamics coupling analysis in equation form.[54–56]

According to the centralized modeling approach, a multi-link AM system is as shown in Fig. 9. Σ_0, Σ_I, Σ_E, and Σ_i are, respectively, AM body-fixed frame, earth-fixed inertial frame, end-effector frame,

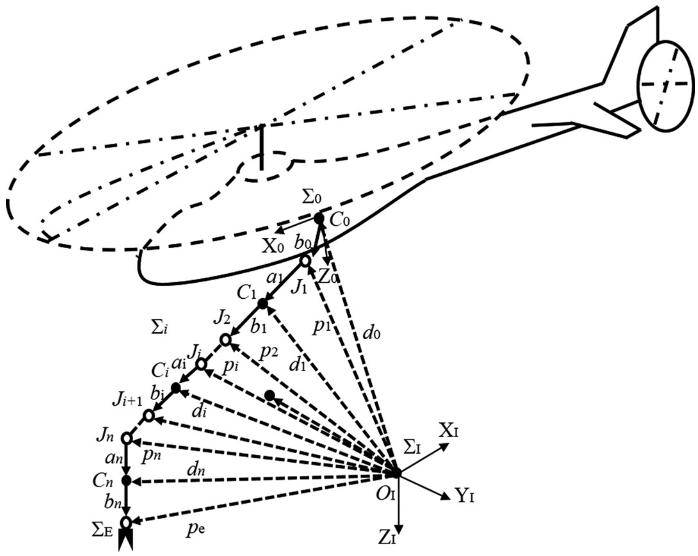

Fig. 9. Frames of AM system based on the centralized approach.

and the frame of joint i of manipulator. J_i $(i = 1, 2, \ldots, n)$ denotes the joints of the manipulator, $\boldsymbol{p}_i$ denotes its position vector in frame Σ_{I}, C_0 and C_i are CoMs of UAV link and link i, $\boldsymbol{d}_0$ and $\boldsymbol{d}_i$ are position vectors of C_0 and C_{i} in frame Σ_{I}, $\boldsymbol{a}_{\mathrm{i}}$ is the vector from J_i to C_i, $\boldsymbol{b}_0$ is the vector from UAV CoM to the first joint, and $\boldsymbol{b}_i$ is vector from C_i to J_{i+1}.[56]

Define $\boldsymbol{p}_{\mathrm{b}} = [x\ y\ z]^{\mathrm{T}}$ is the UAV absolute position in earth-fixed inertial frame (i.e., $\boldsymbol{p}_{\mathrm{b}} = \boldsymbol{d}_0$ as shown in Fig. 9), $\boldsymbol{\Phi}_{\mathrm{b}} = [\phi\vartheta\varphi]^{\mathrm{T}}$is the UAV attitude (described by yaw-pitch-roll angles), and $\boldsymbol{q} = [q_1, q_2, \ldots, q_{\mathrm{n}}]^{\mathrm{T}}$ is the manipulator joint vector. The direct kinematics $\boldsymbol{A}_{\mathrm{b}}(\boldsymbol{\xi})$ for an AM system can be derived by combining UAV kinematics $\boldsymbol{A}_{\mathrm{b}}$ and manipulator kinematics $\boldsymbol{A}^{\mathrm{b}}{}_{\mathrm{e}}$,[40] and it is

$$\boldsymbol{A}_{\mathrm{e}}(\boldsymbol{\xi}) = \boldsymbol{A}_{\mathrm{b}}(\boldsymbol{p}_{\mathrm{b}}, \boldsymbol{\Phi}_{\mathrm{b}})\boldsymbol{A}_{\mathrm{e}}^{\mathrm{b}}(\boldsymbol{q}) \tag{2}$$

where $\boldsymbol{\xi} = [\boldsymbol{p}_{\mathrm{b}}\boldsymbol{\Phi}_{\mathrm{b}}\boldsymbol{q}]^{\mathrm{T}}$ is the generalized $6 + n$ joints vector of the AM system. Define $\boldsymbol{X}_e = [\boldsymbol{p}_e\boldsymbol{\Phi}_e]^{\mathrm{T}}$ is the AM end-effector pose. Then the Jacobian matrix $\boldsymbol{J}(\boldsymbol{\xi})$ relationship is[78]

$$\dot{\boldsymbol{X}}_{\mathrm{e}} = \boldsymbol{J}(\boldsymbol{\xi})\dot{\boldsymbol{\xi}} \tag{3}$$

In addition, the kinetic energy and potential energy can also be derived,[54] and the final AM dynamics can be obtained through Euler-Lagrange equation as shown here

$$\begin{bmatrix} \boldsymbol{H}_{\mathrm{b}} & \boldsymbol{H}_{\mathrm{bm}} \\ \boldsymbol{H}_{\mathrm{bm}}^{\mathrm{T}} & \boldsymbol{H}_{\mathrm{m}} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{X}}_{\mathrm{b}} \\ \ddot{\boldsymbol{q}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{C}_{\mathrm{b}} \\ \boldsymbol{C}_{\mathrm{m}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{G}_{\mathrm{b}} \\ \boldsymbol{G}_{\mathrm{m}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}_{\mathrm{p}} \\ \boldsymbol{\tau}_{\mathrm{m}} \end{bmatrix} \tag{4}$$

where $\boldsymbol{H}_{\mathrm{b}}$ is UAV inertia matrix, $\boldsymbol{H}_{\mathrm{m}}$ is manipulator inertia matrix, and $\boldsymbol{H}_{\mathrm{bm}}$ is the coupling inertia matrix. $\boldsymbol{X}_{\mathrm{b}}$=$[\boldsymbol{p}_{\mathrm{b}}\boldsymbol{\Phi}_{\mathrm{b}}]^{\mathrm{T}}$ is UAV pose. $\boldsymbol{C}_{\mathrm{b}}$ and $\boldsymbol{C}_{\mathrm{m}}$ are Coriolis and centrifugal force. $\boldsymbol{G}_{\mathrm{b}}$ and $\boldsymbol{G}_{\mathrm{m}}$ are gravity items. $\boldsymbol{F}_{\mathrm{b}}$ and $\boldsymbol{\tau}_{\mathrm{m}}$ are, respectively, UAV aerodynamic force and joint motor driving force.

3.2.2. Control. The overall AM dynamics is multivariable and with strong coupling and nonlinearity. Many control algorithms (including linear and nonlinear) have been applied to it. A full-state feedback linear quadratic regulator (LQR) controller is designed through obtaining linearized model near steady state.[54,55] The simulation result shows that the standard linear LQR controller is able to stabilize the AM system near steady state.[56] However, the stabilization region of LQR controller is very limited, and the performance of LQR controller is sensitive to external disturbance. A nonlinear model-predictive control (NMPC) approach has proved to be effective when an AM performs the pick-and-place task.[81] An adaptive sliding mode controller is used to ensure position holding while the AM picks and releases an object during hovering flight,[107] and experiments demonstrate satisfactory performance.

In addition to system stability control, trajectory tracking control and task-priority-based hierarchical control have been researched. A hierarchical control architecture contributes to solving the

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motion control problem of an AM end-effector even in the presence of non-idealities and model uncertainties.[38] A nonlinear trajectory control technique is effectively applied to a free-flying AM system.[67] A null space based (NSB) controller is proposed to tackle the coordination between the arm and UAV motions.[78] A visual predictive guidance law is tested to steer an AM from the initial position to the appropriate position to grab a target object. A hybrid visual servoing with a hierarchical task-composition control framework is designed for the grasping task.[110,114,131] A decentralized flatness-based controller shows advantages in tracking dynamic maneuvers for an AM in 3D space.[148] A task-oriented control strategy takes into account the hierarchy of tasks by projecting each one into the Jacobian null space of the previous one, and is demonstrated in a simulated case study.[162]

Remark 5. The centralized model clearly shows the dynamics coupling between a UAV and a manipulator, and also provides the overall AM kinematics. However, parameter identification in the high-order, coupling, and nonlinear model is difficult; thus, an accurate physical model is hardly ever obtained, giving rise to a limitation where some control methods can be tested only in simulation. Therefore, some simplified models are usually used for coupling analysis and controller design. Research based on the centralized idea tends to focus more on trajectory planning and task hierarchical control to achieve coordinated motion between the UAV and the arm while conducting aerial manipulation tasks.

4. Motion-Restricted AM Research

When an AM physically interacts with environment to perform contact-based tasks, non-negligible contact force will be exerted by the external environment, and this will be reflected in dynamics, which is the evident difference between free-flight and motion-restricted flight modes.

4.1. Decentralized approach

4.1.1. Modeling. The decentralized modeling method in motion-restricted flight is similar to that in Section 3.1, in which the external force and moment are included. This modeling idea is widely used in existing motion-restricted researches.[8,37,63,84,89,121,146,154,158,165,166] Thus, the dynamics for UAV platform can be expressed as

$$\begin{cases} \dot{\boldsymbol{p}}_{\mathrm{b}} = \boldsymbol{v}_{\mathrm{b}} \\ \dot{\boldsymbol{v}}_{\mathrm{b}} = g\boldsymbol{e}_3 - 1/mF\boldsymbol{R}_{\mathrm{b}}\boldsymbol{e}_3 - \\ \qquad \boldsymbol{R}_{\mathrm{b}}(\dot{\boldsymbol{\omega}}_{\mathrm{b}}^{\mathrm{b}} \times \boldsymbol{r}_{\mathrm{OC}}^{\mathrm{b}}(\boldsymbol{q}) + \boldsymbol{\omega}_{\mathrm{b}}^{\mathrm{b}} \times (\boldsymbol{\omega}_{\mathrm{b}}^{\mathrm{b}} \times \boldsymbol{r}_{\mathrm{OC}}^{\mathrm{b}}(\boldsymbol{q}))) + 1/m\boldsymbol{F}_{\mathrm{e}} \\ \dot{\boldsymbol{R}}_{\mathrm{b}} = \boldsymbol{R}_{\mathrm{b}}S(\boldsymbol{\omega}_{\mathrm{b}}^{\mathrm{b}}) \\ \dot{\boldsymbol{\omega}}_{\mathrm{b}}^{\mathrm{b}} = \boldsymbol{I}_{\mathrm{b}}^{-1}(\boldsymbol{M} - \boldsymbol{\omega}_{\mathrm{b}}^{\mathrm{b}} \times (\boldsymbol{I}_{\mathrm{b}}\boldsymbol{\omega}_{\mathrm{b}}^{\mathrm{b}}) + \boldsymbol{r}_{\mathrm{OC}}^{\mathrm{b}}(\boldsymbol{q}) \times F\boldsymbol{e}_3 + \boldsymbol{M}_{\mathrm{e}}) \end{cases} \quad (5)$$

where $\boldsymbol{F}_e$ and $\boldsymbol{M}_e$ are, respectively, external force and moment introduced by the external environment, and other parameters are the same with those in Section 3.1.

4.1.2. Control. The motion-restricted manipulation requires an AM to physically interact with environment for a continuous time period with a desired force. Therefore, some force control–related techniques are usually applied to maintain the interaction force. A separate position and orientation control on SE Eq. (3) and a hybrid pose/wrench control are applied on ODAR (a new AM platform) to achieve position and force control in contact task (peg-in-hole force feedback teleoperation).[37] An inner-outer-loop control strategy (combined with geometric control and admittance control) is used to control a tilt-hexa-rotor UAV's position and orientation while simultaneously exerting a full-wrench (force and torque independently) on environment with a rigidly attached end-effector.[63] The results of related flight experiments display the stability, accuracy, and dexterity of the AM system for tasks requiring aerial physical interaction. An impedance controller is proposed to help a planar AM to enter into contact with a vertical surface to perform the inspection task.[84] The force experienced at AM end-effector can be adaptively controlled through the use of an actively variable compliance manipulator.[89] A hybrid force/motion control framework is able to ensure that the UAV angular rates are still bounded, thereby preventing finite-time escape while an AM is in interactive operation.[146] An LQR-optimized state feedback is used on UAV roll and yaw angle to stabilize the AM system and to maintain a fixed contact force.[154] The near-hovering controller has proved to be effective when

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an AM is used in contact with the environment to generate a desired contact force.[165] A variable impedance control is presented to control an AM system as well as the interaction force.[166]

Remark 6. The decentralized approach in motion-restricted operation research has simple dynamics form, making it easier to design control schemes. The AM manipulator links are normally designed to be light-weight and compact, and operations are usually performed with lower velocity. Thus, the impact of varying CoM and moment of inertia are often neglected, with the result that the motion-restricted research at present focuses mainly on contact force control (especially fixed or slow-varying contact force). Therefore, some force-related control techniques are naturally applied to the UAV subsystem to achieve the exertion of desired force on external environment through a rigid manipulator link.

4.2. Centralized approach

4.2.1. Modeling. The overall dynamics for a motion-restricted AM system can be obtained using Euler-Lagrange formulation. The generalized state vector includes the DOFs of UAV and manipulator joint variables. The force (including force and moment) vector consists of UAV aerodynamic force, manipulator joint actuator force, and external environment force. This modeling approach is attractive and also popular in motion-restricted research.[40,52,53,68,88,99,100,117,124,126,159,163] The equations in compact matrix form can be written as

$$\begin{bmatrix} \boldsymbol{H}_{\mathrm{b}} & \boldsymbol{H}_{\mathrm{bm}} \\ \boldsymbol{H}_{\mathrm{bm}}^{\mathrm{T}} & \boldsymbol{H}_{\mathrm{m}} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{X}}_{\mathrm{b}} \\ \ddot{\boldsymbol{q}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{C}_{\mathrm{b}} \\ \boldsymbol{C}_{\mathrm{m}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{G}_{\mathrm{b}} \\ \boldsymbol{G}_{\mathrm{m}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}_{\mathrm{p}} \\ \boldsymbol{\tau}_{\mathrm{m}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{J}_{\mathrm{b}}^{\mathrm{T}} \\ \boldsymbol{J}_{\mathrm{m}}^{\mathrm{T}} \end{bmatrix} \boldsymbol{F}_{\mathrm{e}} \tag{6}$$

where $\boldsymbol{J}_{\mathrm{b}}^{\mathrm{T}}$ is defined as UAV subsystem Jacobian matrix, $\boldsymbol{J}_{\mathrm{m}}^{\mathrm{T}}$ is defined as manipulator subsystem Jacobian matrix, and other parameters are the same as those in Section 3.2.[54]

4.2.2. Control. Based on the overall dynamics, the AM system stability and end-effector dynamic contact force control are two areas of focused research. A Cartesian impedance control is employed on an AM system to create a dynamic relationship between external generalized forces acting on the structure and the whole system motion.[40] A passive compliance control is designed for a helicopter AM system to achieve stable environmental interactions.[52,53] Three new image-based visual-impedance control laws are proposed allowing physical interaction of a dual-arm AM equipped with a camera and a force/torque sensor.[100] Strategies utilizing velocity of the end effector are employed to deal with uncertainties coupled with the operation mechanism, and the proposed approach is validated with experiments including opening and closing a common drawer.[117] A multilevel architecture impedance control scheme for an AM is proposed, with the aim of reducing the end-effector interaction forces with the environment.[163]

Remark 7. The centralized approach is based on whole system dynamics and is more accurate than the decentralized model, which contributes to controlling the dynamic contact force and realizing a hierarchical control strategy. However, the overall dynamics is very difficult in model identification and is also complex in control implementation. In practice, some simplified models based on overall dynamics are often used by researchers.

4.3. Closed-loop UAV-based approach

The stable contact with environment, fixed force holding, and variable contact force tracking for an AM poses great difficulty due to the heavy dynamics coupling between UAV platform and manipulator. Moreover, a direct force feedback method usually needs a force sensor, bringing with it some disadvantages such as narrow bandwidth, high noise, complicated application conditions.[173] To avoid these problems, a novel contact force control scheme is proposed as shown in Fig. 10.[36,41]

4.3.1. Modeling. Feedback linearization is applied to UAV system, with which the closed-loop UAV is shown to behave as a spring-mass-damper system as depicted in Fig. 11, and the position responses under external forces are presented as

$$\boldsymbol{X}(s) = \frac{1}{s^2 m + s k^{\mathrm{s}} m + k^{\mathrm{r}} m} \boldsymbol{F}^{\mathrm{ext}}(s) \tag{7}$$

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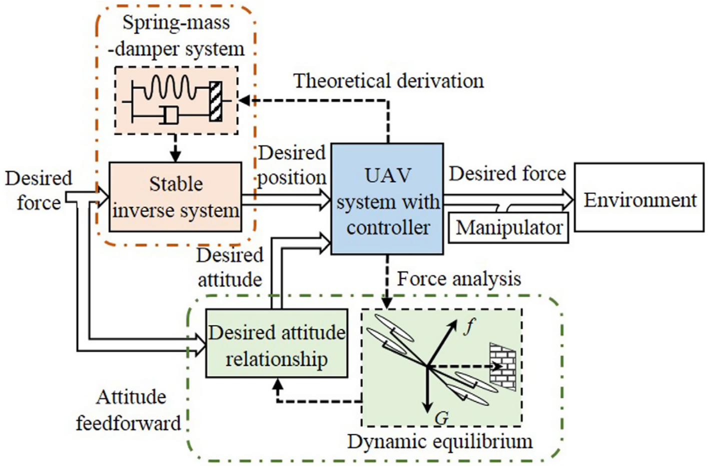

Fig. 10. Overview of the closed-loop UAV-based approach.

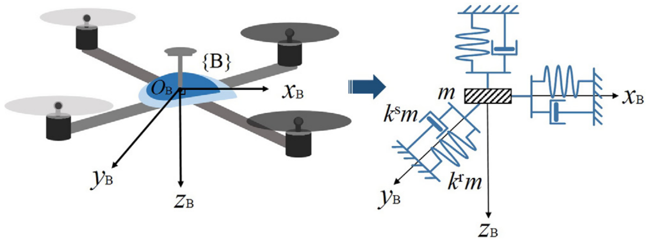

Fig. 11. Hovering UAV acts as a spring-mass-damper system.

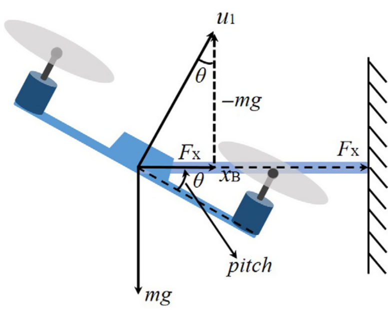

Fig. 12. An aerial manipulator contacts with a wall.

where $\boldsymbol{X}$ is UAV position in earth-fixed inertial frame, $\boldsymbol{F}^{\text{ext}}$ is the external environment force, m is the overall AM system mass, and k^{s} and k^{r} are UAV controller parameters.

For a common spring system with one fixed end, the force exerted on the other end is known to linearly relate to its position change. According to relationship Eq. (7), a closed-loop UAV also has the spring-mass-damper-like characteristics. Thus, the AM force control problem can be considered to be transformed into a position control issue.

Owing to the under-actuation property of rotorcraft UAVs, when an AM exerts a forward horizontal force on wall surfaces, the actual force form is shown in Fig. 12. The contact force F_{x} can be expressed with UAV attitude angle ϑ and gravity mg, and it is

$$F_{\text{x}} = -mg\tan\theta \tag{8}$$

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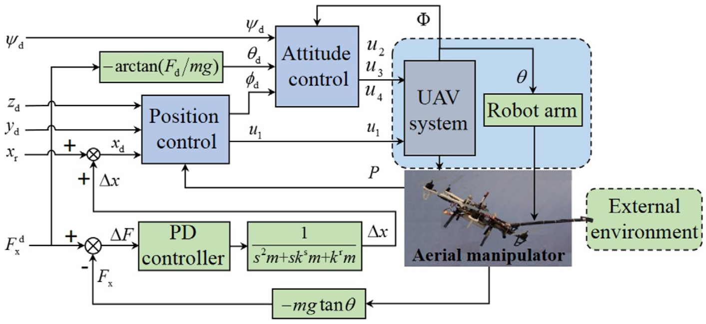

Fig. 13. Contact force control block diagram of AM.

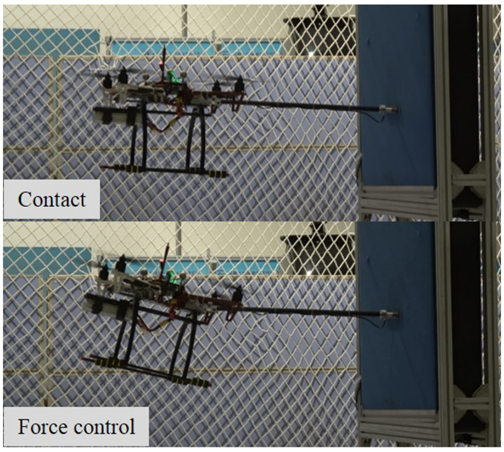

Fig. 14. The contact force control experiment with a quadrotor AM.

Corresponding with the tilt angle, the forward exerted force has a matching pitch angle ϑ, as depicted in Fig. 12. If the contact force is the desired value ${F_x}^d$ in force control, the matching ϑ is thus the desired pitch angle ϑ_d, which can be obtained based on Eq. (8) and it is

$$\theta_d = -\arctan(F_x^d/mg) \tag{9}$$

According to Eq. (8), an aerial manipulator system could act as a force sensor in contact operations, which means the contact force control can be implemented without direct force feedback (a physical force sensor is not required). When an AM exerts a horizontal force on external environment, based on Eq. (9), the desired force ${F_x}^d$ can be quantified by UAV attitude angle, which means the force can be achieved as long as the attitude reaches the desired value ϑ_d.

4.3.2. Control. The impedance control idea shows that robot force control can be transformed into a position issue with desired impedance relationship.[174] Based on Eq. (7), the closed-loop UAV behaves as a spring-mass-damper system, and it has its own stiffness and damping. Thus, the AM contact force control is also transformed in physical implementation, and the control block diagram is presented in Fig. 13. A PD controller is used to improve its performance. Furthermore, Fig. 12 shows the contact force can be acquired without relying on a force sensor, and the real-time contact force is obtained by Eq. (8). In addition, to improve the tracking performance of dynamic contact force and implement variable force control, an attitude feedforward scheme is designed based on Eq. (9), as depicted in Fig. 13.

4.3.3. Experiment. The ramp force tracking and constant force control experiment with a quadrotor AM system is presented to validate the proposed method,[175] as depicted in Fig. 14.

The contact force control result is provided in Fig. 15, and the real-time contact force error is shown in Fig. 16.

Table II. Mean and variance of contact force.

Item	$\Delta F_{mes} = F_{mes} - F_{des}$		$\Delta F_{cal} = F_{cal} - F_{des}$
Mean	0.1328 N	>	0.0353 N
Variance	0.0867 N^2	>	0.0438 N^2

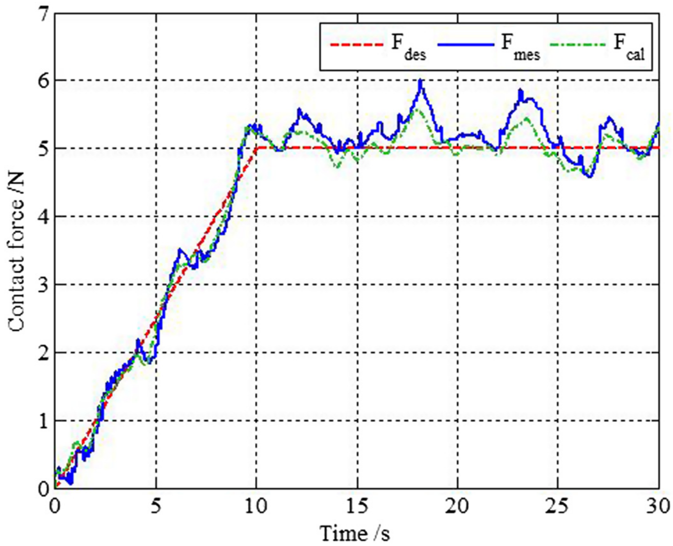

Fig. 15. Ramp force tracking and constant force control.

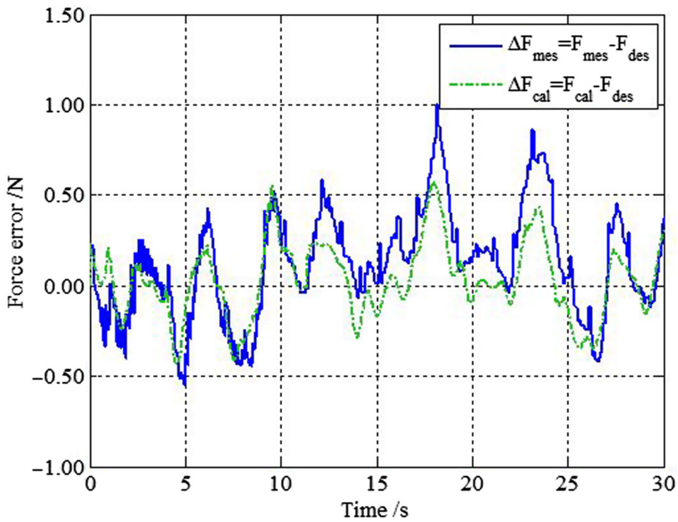

Fig. 16. The real-time contact force error.

F_{mes} is the actual contact force measured by the force sensor, F_{cal} is the calculated force obtained from relationship Eq. (8), and F_{des} is the desired control force. Corresponding with Fig. 16, the mean and variance of force error $\Delta F_{mes} = F_{mes} - F_{des}$ and $\Delta F_{cal} = F_{cal} - F_{des}$ are calculated and shown in Table II.

The result shows that the response for ramp force is quick, and the constant force control can also be achieved. Moreover, the contact force obtained from an onboard force sensor (F_{mes}) inevitably has high noise and delay, which is mainly caused by the soft structure of the strain gauge and UAV hover vibration. This will reduce the system performance if the direct force feedback is used in force control loop. However, for the calculated force (F_{cal}) from Eq. (8), UAV mass can be easily measured, and

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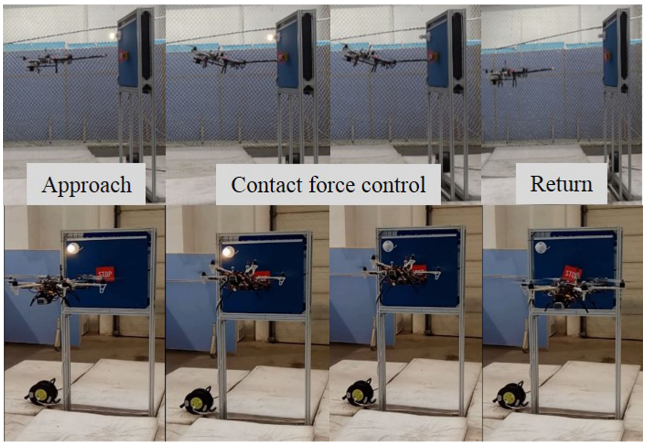

Fig. 17. The process of pressing an emergency switch.

UAV attitude angle is obtained through data fusion of multiple high-precision motion sensors (e.g., Inertial Measurement Unit and magnetic compass). Therefore, its value has less noise and delay than a regular force sensor. This is why the force sensor data are not used in control loop design in our method.

A hexrotor AM system is applied to the operation of pressing an emergency switch to switch off a light. The whole process is divided into several steps: take-off, approach target, contact target, contact force control, return, and land. The main steps are depicted in Fig. 17.

The experimental results show the feasibility and validity of the proposed method, and its novelty is in the following two aspects: (1) the force control is implemented without any force sensor and (2) the whole control scheme is applicable for both fixed and variable contact force control with high closed-loop performance.

5. Challenge and Future Research

As a new robotic system, AM displays great potential in many applications, such as canopy sampling,[116] power grid maintenance,[104] and bridge inspection.[125] However, its utility in more applications is yet to be established because there are still some challenging problems that need to be researched deeply. In this section, some basic theory and technological problems of the future are presented and analyzed.

5.1. Application-oriented platform design

Although the AM has great potential to conduct versatile tasks, most current work still focuses on the basic capacity tests. To design a practical AM system, a proper and optimized platform with respect to special tasks is still the foremost challenge.

1) Task compatible RUAV platform—Different RUAV platforms present different characteristics as well as different disadvantages. For example, the helicopter can take much more payload, but it is difficult to ensure its steadiness; the multi-rotor aircraft flies more steadily but is usually unable to operate heavy targets. Up to now, few researchers have considered designing new flight platforms to improve the operational performance. This, however, may become an important topic in this field because the operational mechanisms will simultaneously "influence" and "help" the AM systems.
2) Task compatible operation mechanisms—Most of the existing AMs are equipped with universal and commercial manipulation mechanisms, which are not typically designed for aerial operation and thus present many disadvantages. Most recently, some research has appeared about specially designed manipulation mechanisms, such as I-BoomCopter[60] and AGRASP.[75] Unfortunately, most of these work is implemented only in lab environments, and both theoretical and engineering factors should be considered to find more efficient operation mechanisms.

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5.2. Modeling and control

A regular RUAV possesses unfavorable characteristics such as nonlinearities, strong-coupling, under-actuation, and sensitivity to disturbance. The same is true for the AM system as a typical multi-rigid-body system moving freely in 3D space. While the operation mechanism significantly enlarges these effects, many modeling schemes have been researched and present different advantages and disadvantages. Modeling, especially control oriented modeling, will still be an important researching focus of research in this topic, and there may be two directions of research as follows:

1) Fusion of Multiple Models—In different states and modes, the AM presents differentiated characteristics. Unfortunately, in many tasks, the AM system needs to work across several modes. Thus, it is important to find a proper scheme to fuse multiple models so that control becomes easy for the complete task procedure.
2) Modeling for physical interaction task—Physical interaction task is special and difficult because it requires the AMs to interact with the external environments continuously or discontinuously. This will introduce some uncertainties that will be difficult to model, and thus new schemes are necessary to describe this type of phenomenon.

As far as control algorithms are concerned, a variety of control algorithms have shown their efficiency, including model-based methods and model free methods. The model-based methods are mostly validated in simulation, wherein only a small part of controllers are tested by actual flight experiments. The main reason is that accurate physical model parameters are difficult to acquire. The model free (or simplified model based) method has been shown to be useful in many practical experiments, but it possesses evident weaknesses and inadaptability especially when facing high maneuverability cases and high-accuracy requirements. In future work, the following two points are important for control of AM system:

1) Robustness of the controller—Robustness is of great importance for any control problems. For any AM system, the controller should present its robustness with respect to at least two aspects: the first is the coupling between the flight platform and the operational mechanisms, which is more difficult when dynamic tasks or high speed states are required; the second is the external disturbances including winds, and physical contact force, which is important to ensure the operational safety.
2) Control scheme and structure for special tasks—Currently, most of AM research is aimed at simple or quasi-static tasks including grasping and pick-and-place. However, AM systems will possibly be able to conduct much more complicated, dynamic, or even high maneuver tasks as high speed like agile targets capture, perching at special places, as well as some special tasks such as building surface detection and cleaning for which the AM is required to be in continuous contact with the target.

5.3. Perception, decision, and HRI

Perception is an important and open problem for almost all types of field robotics. As far as AM is concerned, although some outdoor flight experiments have been conducted using D-GPS, computer vision, or even SLAM techniques, much more current research can only be implemented in lab with ideal perception schemes like motion capture system. Usually, precise operations require accurate perception. These are still difficult in reality, including inner state sensing, such as flight states and operational mechanism states, and environmental state sensing, such as target states and surroundings. What is more important is that precise and proper force measurement and sensing are also difficult but necessary with respect to the physical interactions class task. The research in this field is still abstract.

As a manipulation device, decision making capability is very important because most manipulation tasks need to divide the complete task into some subtasks and then find an optimal procedure to execute. Currently, most related research focuses only on the capability design of the AM system with respect to the specific task but fails to consider the complete task procedure. In the future, it will be necessary to make the AM system "smart" enough to decide how to conduct a task under some practical constraints.

Another possible topic of research is how to use machine intelligence algorithm in AM system. Machine intelligence has gradually become a popular and useful idea to increase the autonomy of robot systems. In addition to some common intelligent techniques (e.g., autonomous model structure learning and parameter optimization, learning-based recognition, and planning and decision), the task-level intelligence is of great importance for AM system to learn some new manipulation skills.

For more complicated tasks that cannot be completely executed by an AM system itself, the introduction of human intervention becomes necessary. That means, HRI is also an important subject of research in this field. For example, let us say we want an AM to complete a routine task of an industrial robot: drilling and screw twisting on a vertical wall. This task can be broken down into several subtasks such as: (1) maintaining steady contact in flight, (2) exerting a desired force, and (3) drilling and screw twisting. Remote control is more feasible for these types of tasks. However, as a special mobile robot system, it is very difficult to ensure the stability of the AM during HRI, and improper intervention may introduce new security threats.

6. Conclusion and Future

This article presents the research and development of AM systems during the past decade. The AM system structure is introduced from UAV platforms and manipulation mechanisms. Moreover, the existing aerial manipulation tasks are grouped into two categories: free-flight operation and motion-restricted operation, and different modeling and control approaches for these two operations are presented, respectively. The worldwide influential research groups and representative work of these groups are summarized and classified. Conclusions for existing research and some future challenges are shown.

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