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Citation for the original published paper (version of record):

Ding, X., Guo, P., Xu, K. et al (2019). A review of aerial manipulation of small-scale rotorcraft unmanned robotic systems. Chinese Journal of Aeronautics, 32(1): 200-214.
http://dx.doi.org/10.1016/j.cja.2018.05.012

Chinese Journal of Aeronautics, (2019), **32**(1): 200–214

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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A review of aerial manipulation of small-scale rotorcraft unmanned robotic systems

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Received 19 October 2017; revised 10 January 2018; accepted 30 May 2018
Available online 22 June 2018

KEYWORDS

Aerial manipulation;
Mechanical structure design;
Modeling and control;
Research groups;
Small-scale rotorcraft unmanned aerial systems;
Trends and challenges

Abstract Small-scale rotorcraft unmanned robotic systems (SRURSs) are a kind of unmanned rotorcraft with manipulating devices. This review aims to provide an overview on aerial manipulation of SRURSs nowadays and promote relative research in the future. In the past decade, aerial manipulation of SRURSs has attracted the interest of researchers globally. This paper provides a literature review of the last 10 years (2008–2017) on SRURSs, and details achievements and challenges. Firstly, the definition, current state, development, classification, and challenges of SRURSs are introduced. Then, related papers are organized into two topical categories: mechanical structure design, and modeling and control. Following this, research groups involved in SRURS research and their major achievements are summarized and classified in the form of tables. The research groups are introduced in detail from seven parts. Finally, trends and challenges are compiled and presented to serve as a resource for researchers interested in aerial manipulation of SRURSs. The problem, trends, and challenges are described from three aspects. Conclusions of the paper are presented, and the future of SRURSs is discussed to enable further research interests.

1. Introduction

The use of small-scale rotorcraft robotic systems (SRURSs) is increasing rapidly in both scientific[1] and commercial fields. We typically define small-scale as being lighter than 25 kg or smaller than 10 m in any dimension;[2] rotorcraft refers primarily to helicopter and multirotor in this paper. In commercial fields, SRURSs are typically used for photography, agriculture, disaster monitoring, environmental surveillance, nuclear disaster response,[3] and electric power inspection. The United Business Media (UBM)[4] has indicated an approximate 40% increase in unmanned aerial vehicles (UAVs) during 2017–2018, similar to 2016–2017. It has been reported that approximately 587,000 UAVs were sold in 2015. In scientific fields, SRURSs are widely used for unknown environment modeling,[5] data acquisition,[6] and manipulation.[7] Compared to commercial SRURSs, scientific researchers interested in manipulation are more concerned with interaction with the environment. The physical interaction with the surrounding environment pre-

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.05.012
1000-9361

sents a greater challenge to researchers, the most significant problem being the coupling between aerial platforms and manipulating devices. Aerial manipulation is creatively used in construction,[8] drawer operation,[9] object transporting,[10,11] valve turning,[12] tool operation,[13] ultrasonic testing,[14] unknown environment sensing,[15] bulb screwing,[16] bridge inspection,[17] wall climbing,[18,19] aerial writing,[20] perching and charging, anti-UAV combatting, delivering, and object assembling.

Searching for keywords in the Web of Science Core Collection,[21] it is observed that research related to UAVs and aerial manipulation has increased rapidly since 2011 as indicated in Fig. 1. Performing a second search using specific keywords such as quadrotor and grasping indicates that from 2008 to September 2017, only 145 papers related to aerial manipulation were retrieved out of 8373 papers as displayed in Fig. 2. However, there have been workshops at the top conference on robotics, namely the IEEE International Conference on Robotics and Automation (ICRA), every year from 2014 to 2017.[22–25] It is clear that the potential of aerial manipulation is high, and it remains both a frontier and valuable research direction.

With the development of aerial robot platforms, the demand for aerial robots is no longer confined to observe the environment in a passive manner. Aerial robots offer the abilities of rapid maneuvering and dexterous manipulation under complex working conditions and dangerous environmental conditions. Aerial manipulation can be summarized into two problems: flying and manipulating. Further, it typically consists of two types, floating base-like multirotor and actuator-like manipulator. SRURSs manipulating devices can be divided into four categories: gripper, multi-degree of freedom (DOF) rigid-body aerial manipulator, aircraft with a suspended load attached through a cable or tether, and others such as airframes or anthropomorphic fingers. Manipulation methods can be divided into four categories: grasp, interact, hang, and manipulate.

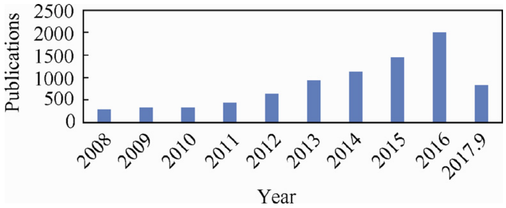

Fig. 1 Publication search results in the Web of Science Core Collection.

Universities and research institutions in the United States are typically sponsored by the National Aeronautics and Space Administration (NASA),[26] Defense Advanced Research Projects Agency (DARPA),[27] National Science Foundation (NSF),[28] Office of Naval research (ONR),[29] and other organizations. Universities and research institutions in Europe are commonly sponsored by projects from Horizon 2020[30] and the 7th Framework Programme (7FP)[31] such as AIRobot,[32] ARCAS,[33] SHERPA,[34] and Aeroworks.[35] Other universities and research institutions are largely sponsored by foundations in their own countries such as the National Natural Science Foundation of China (NSFC)[36] and the National Research Foundation of Korea (NRF).[37] Because of the different requirements of sponsors and different development ideas of research institutions and universities, they typically proceed in a diverse directions.

Moreover, the development of UAVs has been further encouraged by UAV competitions. The MBZIRC 2017[38] competition was successfully held in March 2017. Challenge 3 required a team of UAVs to collaborate to detect, locate, track, pick up, and place down a set of static and moving objects. The organizers offered five million dollars in prizes and sponsorships. The upcoming MBZIRC 2019 Challenge 1 is based on UAV dynamic aerial tracking and interventions in 3D. It will require a team of UAVs to autonomously locate, track, and interact with a set of objects moving in space.

The first challenge of SRURSs when prototypes are developed is the mechanical structure design, which is both signifi-

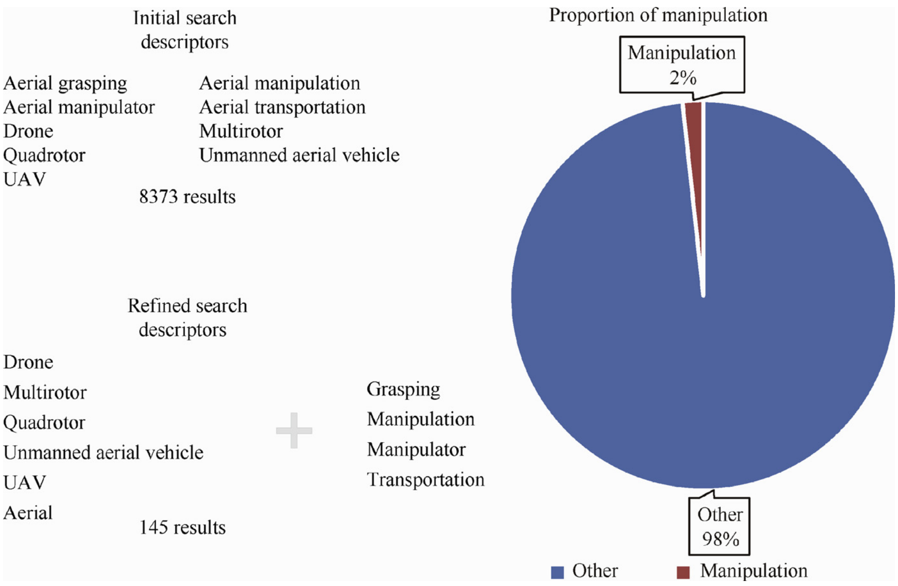

Fig. 2 Article comparison between two searches.

cant and interesting. Researchers globally have proposed many different ideas (see Section 2) including LEGO toys,[39] avian-inspired designs,[40] compliant designs,[15] anthropomorphic designs,[41] fault-tolerant designs,[42] Delta mechanisms,[14] parallel mechanisms,[43] redundant designs,[44] tool designs of collaborative work,[45] KUKA manipulators,[46] vacuum pump self-sealing suctions,[47] and SHERPA grippers.[48] The primary consideration is the mechanical configuration design, because the movement of a manipulating device critically influences a UAV. A superior mechanical structure can reduce the complexity of the controller and coupling between the UAV and the manipulating device, hence improving the capability of SRURSs.

The major challenges in aerial manipulation are modeling and control. There are two approaches to address modeling and control problems. The first independent approach divides a system into two independent parts and considers the modeling methods of each part respectively. This approach considers the motion and dynamics of manipulating devices as external disturbances of UAVs; hence, it is easier to implement than an alternative. The second is an overall approach. It considers the complete system as an overall system, addressing challenges that the center of mass (COM) is changing constantly and the internal dynamics are coupled. The details of these two methods are introduced in Section 3.

To the authors' knowledge, this is the first time that a summarized review of aerial manipulation has been prepared. To provide an overview of the progress of aerial manipulation, achievements from researchers located globally are introduced in detail in Sections 2 and 3.

This paper is composed of six sections. The mechanical structure design of manipulating devices is introduced in Section 2, because the structure is the basis of control. Modeling and control methods are presented and compared in Section 3. In Section 4, works of principal universities and research institutions are presented in a tabular form. In Section 5, trends under multiple conditions and main aerial manipulation research challenges facing researchers are summarized. Finally, Section 6 provides conclusions and thoughts regarding the future of aerial manipulation.

2. Mechanical structure design

As mentioned above, manipulating devices can be divided into four types: gripper, manipulator, cable, and others. They are different from each other mechanically and regarding modeling and control, based on suitability for different application scenarios. The following subsections introduce these manipulating devices in detail.

2.1. Gripper

As displayed in Fig. 3, a single-DOF gripper is the most widely used manipulating device. It is attached directly on or under the airframe of a UAV. This kind of manipulating device has three advantages: (i) easy to build, (ii) convenient modeling and control, and (iii) relatively inexpensive.

To reduce costs, a low-cost, custom-built quadrotor was presented,[39,49] which used a LEGO[50] gripper to reduce the time of prototype development. It gripped a stuffed toy, weighing 150 g, 50 cm below the quadrotor using the gripper. Several grippers including impactive and ingressive grippers have been designed to grasp a number of different items including a beam and a flat piece of wood.[51] Impactive grippers demand that the freedom of the object to be grasped is adapted to the grippers; ingressive grippers are divided into actively engaging and passively engaging. A quadrotors team achieved a construction task using the gripper mentioned above as demonstrated.[8] A group of on-board vacuum suction cups was utilized to grasp a series of objects such as a battery and a hair brush,[47] including items on inclined surfaces. A mechanical coupling was used to reduce the complexity of the grasping mechanism on an adaptive underactuation gripper for a helicopter.[42] Furthermore, a gripper mounted on a helicopter and a quadrotor are compared; results indicated that the quadrotor could fulfill the condition of the gripper mounted above the airframe.[52] A "screwing bulb" experiment was performed by a multirotor with a gripper mounted above the airframe,[16] and an onboard FPGA was used to address the camera information.[53,54] An avian-inspired passive mechanism for a quadrotor and helicopter perching was presented;[40,55] the gripper consisted of three fingers imitating a songbird. Every knuckle was designed independently different from the others on the same finger so that the finger's stiffness was most suitable for perching and grasping; however, the UAV on which the gripper was mounted did not actually move. A dynamic surface grasping technique was proposed for micro-UAV landing and perching; gecko-inspired directional adhesives were used to absorb the collision energy and provide secure perching. A dynamic model that predicts attachment conditions was presented.[56–58] A switch between climbing and perching modes was proposed, and the task of crawling on the wall was realized. A climbing mechanism was designed to allow a robot to recover from a climbing failure.[19,59]

Fig. 3 Example of SRURSs with a gripper from Yale University (picture from Ref. [52]).

As stated above, a gripper has the following disadvantages owing to its mechanical structure: (i) limited workspace and (ii) limited grasping ability of mass and volume.

2.2. Manipulator

A manipulator consists mainly of two parts: one or more multi-DOF arms attached to a UAV's airframe and grippers with different kinds of sensors as illustrated in Fig. 4. Typically, arms and grippers are driven by servomotors. A manipulator significantly expands the workspace compared to a gripper, and can utilize the redundancy of the manipulator to compensate for the position error of a UAV's motion. It is a better choice for complex tasks.

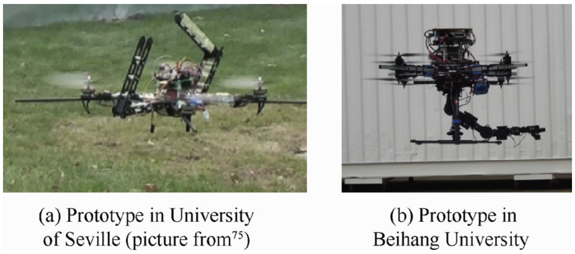
(a) Prototype in University of Seville (picture from[75])
(b) Prototype in Beihang University

Fig. 4 Examples of SRURSs with a manipulator.

A typical robotic arm of a manipulator is a series-connected structure. Different-DOF arms have been developed for different applications. An avian-inspired 1-DOF arm was applied under a quadrotor to achieve bird-like grasping.[60,61] A simple 2-DOF arm was used to grasp a bottle in an indoor environment adopting VICON[62] markers,[63] which could manipulate an object in front of a UAV. Another 2-DOF arm was utilized for picking up and delivering an object, also under a VICON environment, in a dependent and cooperative manner.[10,64,65] Faced with the challenge of turning a valve for the DARPA Robotics Challenge (DRC), a dual 2-DOF arm was applied to a quadrotor;[12,66] the workspace of a UAV-manipulator system was beneath the UAV, and a target was located by visual servoing. With the assistance of a dual 2-DOF arm, a UAV achieved wall-climbing in a walking mode with a mechanical structure, but only in simulations.[18,67,68] Drawer and cylindrical objects under and in front of a multirotor were manipulated with a 3-DOF robotic arm using VICON and vision to locate a UAV and a target.[9,69,70] Another 3-DOF arm was used to accomplish a bridge detection task by contacting from the underside;[17] the arm was mounted on a UAV according to the property of the task. Aimed at improving the dexterity of a robot arm and compliance of joints, a lightweight compliant 3-DOF robotic arm was designed;[15,41] the mechanism of the elbow joint was based on an extension spring to realize collision detection, obstacle detection, and quality estimation of captured objects. Later, the mechanism of the elbow joint was improved by a simple transmission mechanism consisting of a pair of compression springs and a flange bearing.[15] A dual 3-DOF arm flying test was performed.[71] A novel mechanism considering the counterweight between a moving battery and a 6-DOF robotic arm was presented; [72] a flying and manipulating experiment was performed.[73,74] A 7-DOF robotic arm was installed on an octocopter to perform outdoor grasping experiments.[75,76] A fully actuated 7-DOF KUKA redundant industrial robotic arm was used for grasping objects utilizing its redundancy on a helicopter.[46,77,78] A 9-DOF hyper-redundant has been designed for aerial manipulation;[44] however, flying experiments have not yet been performed. Further, parallel manipulators have been applied on UAVs.[43]

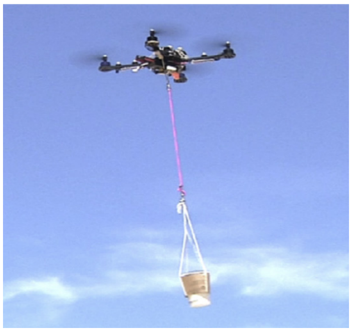

Fig. 5 Example of SRURSs with a cable from University of New Mexico (picture from Ref. [94]).

A manipulator's disadvantages can be concluded as follows: (i) complex mechatronics system, (ii) heavy weight; (iii) difficult to control, and (iv) severe coupling interference with a UAV.

2.3. Cable and others

As displayed in Fig. 5, a cable or tether attached to a UAV is widely used in transporting;[79–82] however, only few of its mechanisms have been considered. Multi-aerial robotic manipulation experiments with cables or tethers were presented.[83,84] Researchers consider more the problem of how a slung-load's motion changes a system's COM and regard this as a control problem. For example, a reinforcement learning approach was adopted.[85] It will be introduced in detail in Section 3.

Many other manipulating devices have been presented by researchers globally. A novel mechanical design of a UAV's manipulating device was presented to interact with the environment and perform ultrasonic nondestructive experiments;[14,86–88] the mechanism consists of a 3-DOF Delta, a Cardan gimbal, and an end-effector. Anthropomorphic grasp was discussed to reduce the effects of gravity and inertia during a grasping process.[89] A novel aerial manipulation system was proposed to perform a tool operation task; the system was developed with multiple quadrotors connected to a tool through spherical joints.[90] A transporting express by a commercial company using a multirotor airframe was tested.[91] A flexible mechanism composed of active joints and passive linear joints was designed, which converts kinetic energy into potential energy; the energy is stored in a directional locking mechanism to reduce the impact of a UAV towards a wall.[92,93]

From the above, a cable or tether is most suitable when attention is paid to the control problem while manipulating. A gripper is easier to implement than a manipulator from the mechanical aspect. Further, a manipulator is rather

Table 1 Comparison between different manipulating devices.

Manipulating device	Cost	Difficulty	Available range	Stability	Application trend
Gripper	Low	Low	Low	High	Decrease
Manipulator	High	High	High	Middle	Rapidly increase
Cable and tether	Low	Suitable	Middle	Middle	Slowly decrease
Other	N/A	High	High	Middle	Increase

difficult compared to other manipulating devices. Manipulating devices are compared in Table 1.

3. Modeling and control

In early works, because the masses of manipulating devices (mainly grippers) and targets were relatively smaller than those of UAVs, researchers ignored the changes of the COM and inertia during a manipulating period; a flying controller was applied directly on the new aerial manipulation system. This could seem as one kind of ‘‘overall approach” in this paper. However, this is a simple and inexact modeling approach. It is called a simplified approach.

The independent approach separates a UAV and manipulating devices apart, and then builds models and controllers separately. As a result, the coupling between the UAV and manipulating devices is regarded as an interference problem.

This overall approach considers the coupling problem as an internal problem; it is extremely accurate and strict. The system model should be integral from the start of kinematics and dynamics modeling.

3.1. Independent approach

The independent approach utilizes the existing control algorithms of a UAV and manipulating devices, and modifies them to adapt the dynamics of a combined system. Hence, it reduces the time required for research. Moreover, the dynamics model of a system is not as complex as that of the overall approach; the interaction force is considered as external interference. This approach simplifies the modeling and control process.

A quadrotor model and a suspended load model were developed independently; a technique based on dynamic programming (DP) and an adaptive controller compensating for the change in the COM caused by load movement were proposed to ensure swing-free trajectory tracking.[79,95] To overcome the DP algorithm’s shortcomings of demanding accurate modeling and trajectory planning in advance, reinforcement learning algorithms such as AVI and LSPI were presented to generate trajectories with minimal residual oscillations for rotorcraft transporting suspended loads.[85,96]

The joint position’s motion range was determined by analyzing the stability change of a UAV originated from a manipulator’s movement.[97]

The model of an outer loop controller for helicopters and load was replaced by a simplified model based on interconnected mass points. For the first time, an experiment with three helicopters with suspended load transporting was performed in 2007.[83,84]

The redundancy of a 7-DOF manipulator was used to reduce the change of a system’s COM when the manipulator was moving. To address the coupling between the airframe and the manipulator, yaw was introduced into kinematic planning of the manipulator. A flying test by combing impedance control with visual servoing control on a helicopter with a 7-DOF KUKA manipulator was performed.[46,77,78]

The contact model was divided into three parts, i.e., a quadrotor, a manipulator, and an environment, which were then combined by the contact point relationship. The attitude and position of the system were tuned by an impedance controller designed according to the passive characteristics of the system.[86] To solve the unstable problem of inner-loop dynamics caused by a former impedance controller, a modified impedance controller combines virtual quality with the external force dynamic model of a system. The mode of a manipulator was divided into a free-flight mode and a contact mode; a hybrid control method was used to switch between the two modes.[87,88,98] An LQR-optimized approach was proposed to replace the traditional PID control and to adapt the condition that forces acting consistently on the wall are similar to the UAV’s weight; however, the algorithm requires the contact point be static.[92,93]

A controller based on momentum estimation considering external forces was proposed; the gain of the estimator was chosen according to the closed-loop impedance behavior with a proper hierarchical structure.[99] The multilayer structure of the controller based on PID was presented.[72]

A variable parameter integral backstepping (VPIB) algorithm replaces PID control for compensating the motion of a manipulator. This controller guarantees asymptotic stability and has robustness to some uncertainties. Experimental results demonstrated that the VPIB controller was superior to the PID on a prototype.[17,100]

The Lagrange dynamics of a system were completely decoupled into two separate parts, the COM dynamics in E(3) and the internal dynamics between the quadrotor and the manipulator. Further, a backstepping-like controller was presented to track the trajectory of the end-effector.[101]

The trajectory linearization control (TLC) for a quadrotor and the inverse kinematics for manipulators were combined to achieve wall-climbing; the interaction between the main body and manipulators was reduced by an optimal planning strategy.[18,68]

3.2. Overall approach

The overall approach is divided into two parts in this paper as described in the following subsections, the simplified and overall approaches. The simplified approach directly applies the traditional control algorithm of a UAV to SRURSs, which is simple and easy to implement, but inaccurate. It is regarded as the early version of the overall approach. The overall approach considers SRURSs as a whole, yet complex.

3.2.1. Simplified approach

The estimates of the mass and offset COM of a system in the PID controller for a quadrotor with a gripper were presented.[51] A construction task was accomplished using the wavefront raster algorithm by the quadrotors team.[8] Avian-inspired perching and grasping based on vision in a GPS-denied, VICON-denied environment were achieved.[102,103]

The contact between a helicopter and an environment is equivalent to a 6-DOF spring, and a PID controller was used for the helicopter grasping with a gripper.[104,105] The stabilities of helicopter grasping and quadrotor grasping were compared. Results indicated that the quadrotor was more sensitive to changes in the COM caused by the load; however, it can be applied to situations where the load must be placed above the COM of the airframe.[52,106]

A low-cost, home-built quadrotor grasping with a gripper was presented. A nested PID was used to overcome precise positioning, object sensing and manipulating, and stabilization caused by object interaction.[39,49]

3.2.2. Overall approach

For the first time, a complete dynamic model was developed for a UAV with a manipulator system. A modified Cartesian impedance control exploiting redundancy was presented to overcome the challenges of interference and aerodynamic modeling.[107] All the system dynamics of the coupled UAV and manipulator were considered for the first time. The low-level layer was based on the backstepping-control theory, and the top layer was a visual servoing feedback controller based on an external image.[108] The controller was improved to adapt multi-cooperation SRURSs.[109] A hybrid control system combing visual servoing control with hierarchical task control was applied for aerial manipulation.[110–112]

A hybrid model was introduced to describe a quadrotor with cable-suspended load. Through the differentially flat theory, a nominal trajectory with different constraints was planned, so that the large-area dynamic motion of the quadrotor under the condition of swing load was possible. Then, tracking of the quadrotor's attitude, the load's attitude, and the position in the three-dimensional space was realized by geometric control.[81,113]

A lifting load process was divided into three parts, i.e., setup, pull, and raise, using the related theory of hybrid systems and utilizing a discrete state to determine the key waypoint that must be passed through.[95,114,115] A smooth trajectory was generated using the minimum snap theory,[116] and an adaptive controller was designed by combining geometric control with the least-squares estimation theory.

A system is regarded as a hybrid system that is divided into four phases including flight, arm deployment, adaption, and manipulation phases, and different adaptive algorithms are applied to the different phases to ensure stability. A valve-turning task was achieved by visual servoing control and gain scheduling. A Lyapunov-based model reference adaptive control (MRAC) method was introduced to address the changes of the COM and inertia, as well as the external disturbance during the manipulation.[66,117] The coupling between environment and SRURSs was divided into three categories including momentary coupling, loose coupling, and strong coupling.[118]

Addressing the requirement that different tasks require different impedance values, a controller structure that can change the impedance and adjust the contact force was proposed. Further, a free-flight controller was proposed to reduce the dependencies on position restrictions and lightweight manipulators.[119,120]

A rigid multi-body system was modeled on the Lie group, and optical trajectory control for aerial manipulation was proposed.[63,121,122]

A modified VPIB algorithm considers full dynamic effects and variation of the mass distribution when a manipulator moves and adopts impendence control. The DGPS and cameras were used to replace VICON. Further, the closed-loop inverse kinematics (CLIK) was used on a SRURS manipulator.[75,76]

A behavioral controller based on null space-based behavioral (NSB) was utilized to integrate the motion between a manipulator and a quadrotor.[73] Another three-layer structure controller was proposed, and a manipulator was controlled by an impedance controller.[74]

A system model from free-flight to contacting on the wall was proposed, and a hybrid-MPC controller to control UAV docking and sliding on the wall was presented. Online data processing for state estimation and manipulating was addressed.[123,124] An aerial writing task was performed based on the hybrid-MPC controller proposed above.[125,126]

An adaptive sliding controller based on a traditional Lagrange modeling method was proposed.[10] An augmented adaptive sliding controller based on a closed-chain robot dynamics was presented for cooperative transportation of multiple SRURSs.[64] Online estimation of objects based on an augmented adaptive sliding controller was proposed.[65] An image-based visual servo (IBVS) for SRURSs was presented to fulfill an indoor manipulation task.[69,70] Parametric dynamic movement primitives (PDMPs) and rapidly exploring randomized trees star (RRT*) were combined to address the multi-SRURS cooperation problem in an obstacle environment.[127] An disturbance-observer-derived external force estimation was proposed to estimate the swing angle of a multirotor-suspended load.[82]

A visual servo control was presented for a multirotor; this processes data online with an onboard FPGA.[16,53,54]

A cable was modeled as an arbitrary number of different links using spherical joints, and a geometric nonlinear controller was used to control the position of the quadrotor with a suspended cable load. Then the model and control methods were applied to arbitrary numbers of quadrotors to achieve manipulation with cables.[128,129]

A coordinate-free dynamics model of a system was used to design a geometric controller to track the position and attitude of a cable-suspended load. An elastic spring model including stiffness and damping was developed to compare with the non-elastic model. Virtually global exponential tracking was achieved.[130,131]

A hybrid model of a system was established by dividing the flight-walking locomotion into three modes including flight mode, double-leg support phase, and single-leg support phase. A globally valid and continuous controller was designed directly on the Lie group for quadrotor manipulating with suspended load.[67,80,132,133]

In conclusion, the independent approach is not sufficiently accurate; however, it outperforms the simplified approach. The overall approach is most accurate, however, also most difficult. Increasingly more researchers are abandoning the simplified approach because its low accuracy can cause instability of SRURSs. The approaches are compared in Table 2.

Table 2 Comparison of different modeling and control methods.

Modeling and control method	Difficulty	Accuracy	Feasibility	Trend
Simplified approach	Low	Low	High	Rapidly decrease
Independent approach	Suitable	Suitable	High	Slowly increase
Overall approach	High	High	Suitable	Rapidly increase

Table 3 Research groups involved in research of SRURSs.

Name of group and institution	Manipulated type	Aerial manipulation platform	Data processing	Implementation approach	Modeling approach	Control method
University of Pennsylvania GRASP Lab[8,51,60,61,81,102,103,113,116,134–138]	Multi gripper cooperation, slung-load, 1-DOF arm	AscTech	Offline	Indoor flight experiment, outdoor flight experiment	Overall modeling	PID, visual servoing
Department of Mechanical Engineering, University of Utah[40,55]	Gripper	Gaui 330X QuadFlyer	Not involved	Indoor experiment	Not involved	Not involved
Department of Electrical Engineering, University of California[39,49]	Gripper	Home-built quadrotor	Offline	Indoor flight experiment	Overall modeling	Nested PID
MARHES Lab, University of New Mexico[79,85,95,96,114,115,139]	Slung-load	AscTec Hummingbird	Offline	Indoor flight experiment	Independent modeling	Geometric adaptive
Department of Mechanical Engineering and Materials Science, Yale University[42,52,104–106]	Gripper	T-Rex600 helicopter	Offline	Outdoor flight experiment	Overall modeling	PID
Drexel Autonomous Systems Lab, Drexel University[43,44,66,97,140]	2-DOF dual-arm, 4-DOF dual-arm	3DRobotics	Offline	Indoor flight experiment	Independent modeling, overall modeling	Adaptive PID, visual servoing
Department of Mechanical Engineering, Johns Hopkins University[63,121,122]	2-DOF arm	3DRobotics	Offline	Indoor flight experiment	Overall modeling	Feedback linearization + PID
RAMS Laboratory, University of Maryland[47]	Multi gripper	AscTech	Offline	Indoor flight experiment	Overall modeling	PID
Biomimetics & Dexterous Manipulation Laboratory, Stanford University[19,56–59]	Multi gripper	AscTech	Not involved	Indoor flight experiment, outdoor flight experiment	Not involved	Not involved
Mechanical and AerospaceEngineering, The George Washington University[128,129,141]	Slung-load	Custom-built quadrotor	Offline	Indoor flight experiment	Overall modeling	Geometric Control
Mechanical Engineering, Carnegie Mellon University[130,131]	Slung-load	Not involved	Not involved	Simulation	Overall modeling	Geometric Control
Real-Time Systems and Robotics, Technical University of Berlin[83,84]	Slung-load, multi-cooperation	Custom-built quadrotor named TUB-H	Online	Outdoor flight experiment	Independent modeling	Model-based control
DLR - German Aerospace Center[46,77,78]	7-DOF arm	SWISS UAV	Online	Outdoor flight experiment	Independent modeling	PID/Impedance control, visual servoing
Laboratory for Robotics and Intelligent Control Systems University of Zagreb[12,117,118]	2-DOF dual-arm	3DRobotics	Offline	Indoor flight experiment	Overall modeling	Gain scheduling + MRAC, visual servoing
CTIT Institute, Robotics and Mechatronics group, University of Twente[14,86–88,92,93,98,119,120,142]	Interaction with manipulator	AsTec Pelican	Offline	Indoor flight experiment	Independent modeling, overall modeling	Impedance control + PID
Autonomous Systems Lab, Swiss Federal Institute of Technology Zurich[20,123–126,143–145]	Interaction with airframe	Custom-built quadrotor named ACX, UPAT-TTR, ASLquad	Offline, online	Indoor flight experiment	Overall modeling	Hybrid MPC
PRISMA Lab, University of Naples Federico II[72,89,99,107–112,146,147]	3-DOF arm, 6-DOF arm	AsTec Pelican	Offline	Simulation, indoor flight experiment	Independent modeling, overall modeling	Cartesian impedance, integral backstepping + image-based visual-servo
Robotics, Vision and Control Group, University of Seville[15,17,41,71,75,100]	3-DOF arm, 7-DOF arm	Custom-built QARM1, ASUME, AMIS	Offline	Indoor experiment, outdoor flight experiment	Independent modeling, overall modeling	Variable Parameter Integral Backstepping

Table 3 (*continued*)

Name of group and institution	Manipulated type	Aerial manipulation platform	Data processing	Implementation approach	Modeling approach	Control method
University of Cassino and Southern Lazio[73,74]	6-DOF arm	AsTec Pelican	Offline	Indoor flight experiment	Overall modeling	Behavioral control, hierarchical control
Intelligent Control Systems Lab, Seoul National University[6,9,10,64,65,69,127,148]	2-DOF arm, 3-DOF arm, Slung-load, Multi-cooperation	Smart Xcopter, DJI F550,Ascending Technologies Firefly	Online	Indoor flight experiment	Overall modeling	Visual servoing, adaptive sliding mode control
Interactive & Networked Robotics Lab, Seoul National University[13,45,90,101,149,150]	Multi cooperation	AscTec Hummingbirds	Offline	Indoor flight experiment	Independent modeling	Backstepping-like control
Department of Robotics, Ritsumeikan University[16,53,54]	Gripper	DJI F550	Online	Indoor flight experiment	Overall modeling	Visual servoing
Space Robot Laboratory, Beihang University[18,67,68,80,132,133,151–154]	2-DOF dual-arm	Custom-built quadrotor named MMAR	Offline	Simulation, outdoor flight experiment	Independent modeling, overall modeling	TLC + computed-torque method

4. Research groups involved in SRURSs' research and major achievements

Numerous research groups have displayed interest in the field of aerial manipulation. Table 3 presents many of the research groups involved in the research and development of aerial manipulation of SRURSs. The majority of these have been introduced in Sections 2 and 3. The list is not exhaustive and excludes military and industrial research groups.

The achievements of these universities and research institutions are listed in Table 4.

From this table, we can observe that research institutions and universities in America are more interested in grippers and cables or tethers, which is a result of their simplicity in implementation, convenient modeling and control, and low cost. Conversely, research institutions and universities in Europe are more interested in manipulators because of the demands of Horizon 2020 and 7FP. The attentions of other research institutions and universities do not express systematic characteristics.

5. Trends and challenges

With the development of aerial manipulation, many types of problems appear when experiments and simulations are performed. To solve these problems, researchers globally present new, exciting ideas. With the ongoing development of research, numerous trends have been formed in many fashions. However, there remain many challenges on how to achieve aerial manipulation. Some of these have been addressed whereas others remain open. These are presented in Fig. 6.

Before undertaking any new research, it is important to build a ground test platform for UAV flying and manipulating. A grasp multiple micro-UAV (MUAV) testbed was introduced, and aerial manipulation was studied on MUAVs with grippers utilizing the testbed.[135] A 6-DOF miniature gantry crane imitating the flight of a UAV with two manipulators was presented.[97] A low-cost, simplified quadrotor test bench for 6-DOF flight was proposed. These test platforms can reduce a research period significantly.[151]

For manipulating devices and DOF choices, researchers are increasingly drawn to two extreme cases. One is the simplest case of a gripper, especially for an MUAV, which faces the challenge of limited manipulating space. The other is a manipulator for the accuracy of manipulation. The challenges they must address are complex modeling and control of SRURSs, and severe interference from a manipulator to a UAV. Both of these cases meet the challenge of how to realize fault-tolerant grasping under the error condition of an end-effector.

The development of hardware and visual algorithms has been rapid in recent years. Aerial manipulation has a strong and special requirement for the hardware of perception as follows. (1) Aerial manipulation with SRURSs demands higher accuracy than a normal UAV. Not only must the UAV be stable, but also the manipulating device and the UAV must be extremely accurate. (2) Aerial manipulation with SRURSs demands lighter payload. This is because the total load capacity of an SRURS is limited, and manipulating devices and payload further reduce the restricted payload. (3) Aerial manipulation with SRURSs demands better sensors. It is important to realize onboard perception and processing; however, the hardware and visual algorithms are limited mainly because of the weight of the hardware and the processing speed. It remains a challenge to achieve complete real-time and accurate perception and processing with onboard sensors. A VICON camera has a strong dependence on the environment, which limits the sizes of SRURSs; it also limits the application scene to indoor locations. VICON is slowly being replaced by visual cameras and DGPS. As processors advance, on-board FPGA and PC104 will facilitate processing data from offline to online. Omitting the data transmission segment such as WIFI and XBEE[155] increases the real-time performance of a UAV. This means that aerial manipulation is moving a step further toward industrial applications and intelligence. There remain three challenges to be resolved for the perception, localization, and data processing problem, which are fusion and filtering of multiple sensors, onboard

Table 4 Major achievements of research groups.

Name of group and institution	Major achievements
University of Pennsylvania GRASP Lab	Constructed with quadrotor teams
	Developed avian-inspired perching and grasping based on vision in GPS-denied, VICON-denied environment
Department of Mechanical Engineering, University of Utah	Developed an avian-inspired passive mechanism for quadrotor perching where the perching remains stable under minor disturbances on a variety of surfaces
Department of Electrical Engineering, University of California	Presented an implementation of autonomous indoor aerial gripping using a low-cost, custom-built quadrotor.
	Overcame major challenges: precise positioning, sensing, and manipulation of an object, and realized stabilization in the presence of a disturbance due to interaction with an object.
MARHES Lab, University of New Mexico	Proposed a technique based on dynamic programming that ensures swing-free trajectory tracking
	Relied on reinforcement learning algorithms such as AVI and LSPI to generate trajectories with minimal residual oscillations for rotorcraft transporting suspended loads
	Designed an adaptive controller combining geometric control and the least square estimation theory, and completed an experiment of lifting objects
Department of Mechanical Engineering and Materials Science, Yale University	Solved the deviations and step disturbances generated due to payload variations and offsets under PID control
	Allowed a UAV to grasp unknown loads within a given mass range
Drexel Autonomous Systems Lab, Drexel University	Constructed a miniature 6-DOF gantry system to provide mobility and emulate a UAV in flight
	Proposed a framework for valve turning using an aerial vehicle endowed with dual multi-DOF manipulators under a visual servoing condition
Department of Mechanical Engineering, Johns Hopkins University	Modeled a rigid multi-body system on the Lie group and proposed an optical trajectory controller for aerial manipulation
	Completed indoor grasp in a NaturalPoint OptiTrack Motion Capture System environment
RAMS Laboratory, University of Maryland	Presented a vacuum pump sucker used as a gripper where a number of suction cups are used to address a variety of problems and different planes of grasping.
Biomimetics & Dexterous Manipulation Laboratory, Stanford University	Proposed a dynamic surface grasping technique for micro-UAV landing and perching, and presented a dynamic model that predicts attachment conditions
	Designed a climbing mechanism. Presented a switch between climbing and perching modes, and realized the task of crawling on a wall. Furthermore, the robot could recover from a climbing failure
Mechanical and Aerospace Engineering, The George Washington University	Modeled a cable as an arbitrary number of different links by spherical joints
	Presented a geometric nonlinear controller to control the position of a quadrotor
	Simulated an arbitrary number of quadrotors to achieve manipulating with cables modeled above
Mechanical Engineering, Carnegie Mellon University	Established a coordinate-free dynamics model of a system by establishing equations of motion directly on the unit sphere and the special orthogonal group. Solved the cooperative transportation problem of multiple quadrotors with a cable
	Developed an elastic spring model including stiffness and damping. Proved that geometric control is applicable to both elastic and non-elastic cables utilizing the singular perturbation theory
Real-Time Systems and Robotics, Technical University of Berlin	Performed the first test flights of three helicopters with suspended load
DLR – German Aerospace Center	Developed a robot with a large helicopter with a real robotic arm
Laboratory for Robotics and Intelligent Control Systems University of Zagreb	Introduced gain scheduling and a Lyapunov-based model reference adaptive control method to address the changes of the COM, inertia, and the external disturbance during manipulation of a robot
	Divided the coupling between environment and SRURSs into three categories including momentary coupling, loose coupling, and strong coupling
CTIT Institute, Robotics and Mechatronics group, University of Twente	Designed a 3-DOF Delta robotic manipulator together with a nondestructive testing end-effector, and performed ultrasonic nondestructive testing experiments
	Proposed a modified impedance control strategy, where a controller uses a virtual mass coupled to a robotic system, which allows for stable interaction
	Presented a versatile control architecture characterized by its capability of varying the apparent impedance of a controlled aerial robot and an interaction force.
Autonomous Systems Lab, Swiss Federal Institute of Technology Zurich	Proposed a real-time simulation suite for coaxial rotor UAVs with interacting environment tasks
	Presented a hybrid-MPC controller to control UAV docking and sliding on walls
	Addressed online data processing for state estimation and manipulating
PRISMA Lab, University of Naples Federico II	Presented a Cartesian impedance control for UAVs equipped with a robotic arm, and exploited the redundancy of the system to perform useful subtasks
	Demonstrated, for the first time, the simultaneous control of a quadrotor and a manipulator it transports considering the internal cross-dynamics.Proposed a new solution for the fast synthesis of anthropomorphic grasps.
Robotics, Vision andControl Group, University of Seville	Designed a light and flexible manipulator for detecting an unknown environment
	Designed a controller that weakens the attitude vibration of four rotors, and improved the control accuracy of the end of the manipulator
	Completed an outdoor flight experiment of a 7-DOF manipulator operation on a UAV

Table 4 (*continued*)

Name of group and institution	Major achievements
University of Cassino and Southern Lazio	Proposed a behavioral control based on the NSB paradigm to address the coordination between the arm and vehicle motions Proposed a controller including three levels, i.e., the outer loop is a trajectory generator and an impedance filter, the middle loop is an inverse kinematic algorithm, and the inner loop is motion tracking
Intelligent Control Systems Lab, Seoul National University	Realized object capture, transportation, and placement under Vicon environment Realized unknown object grasping and transporting through visual capture and online quality estimation Presented a motion planning approach based on PDMPs for coordinating multiple aerial robots and their manipulators quickly in an environment cluttered with obstacles.
Interactive & Networked Robotics Lab, Seoul National University	Proposed a method where the Lagrange dynamics of quadrotor-manipulator systems can be completely decoupled Proposed a hierarchical control framework for multiple cooperative quadrotor-manipulator systems that allows them to endow a common grasped object with a user-specified desired behavior
Department of Robotics, Ritsumeikan University	Described an FPGA-based on-board vision-based control system for autonomous orientation of an aerial robot to assist aerial manipulation tasks such as unscrewing a light bulb
Space Robot Laboratory, Beihang University	Presented a quadrotor test bench that can test and verify a 6-DOF flight controller Designed an MMAR capable of flight and wall climbing based on a TLC controller Addressed the problem of flying-walking locomotion with an MMAR, and employed a hybrid-modeling framework to model the dynamics of the overall flying-walking locomotion maneuver.Investigated the trajectory linearization control for the kinematics on S2 and SO(3). The control is globally valid and continuous because it is designed directly on the Lie group

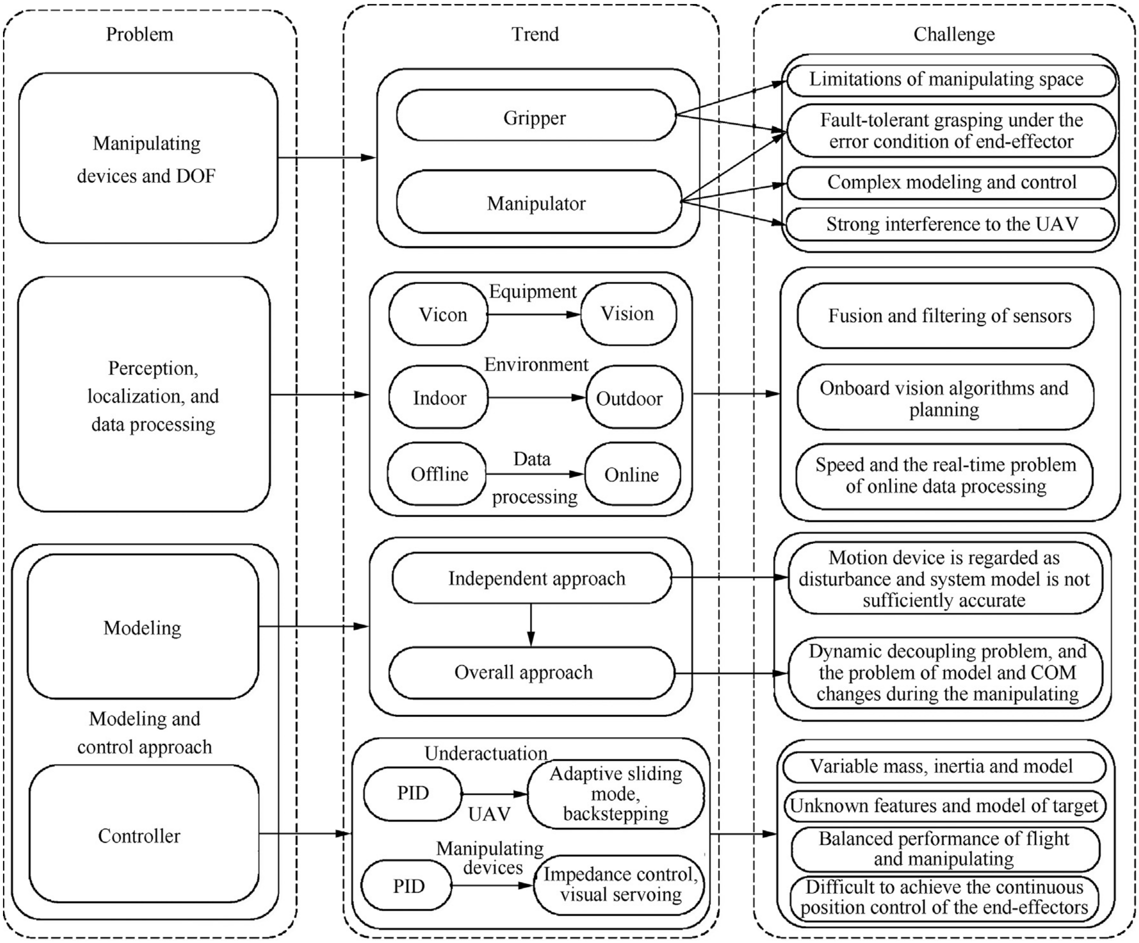

Fig. 6 Problems, trends, and challenges.

vision algorithms and planning, and calculation speed together with the real-time problem of online data processing.

Modeling and control approaches have been introduced in detail in Section 3. Increasingly researchers are adopting the overall approach for high accuracy. The independent approach faces the challenge that the system model is not sufficiently precise. Although the overall approach should solve the dynamic decoupling problem, model and COM changes during manipulating continue. Meanwhile, controllers for UAVs and manipulating devices have been developed from early-time PID to the present situation. Now adaptive sliding mode control and backstepping control are used for UAVs, while impedance control and visual servoing control are used for manipulating devices. A controller should address the following challenges: (i) variable mass, inertia, and model, (ii) unknown features and model of a target, (iii) balanced performance of flight and manipulation, attempting to achieve agile flight with a heavy payload at the same time as providing accurate and stable manipulation, and (iv) continuous position control of the end-effector is difficult to achieve because an underactuated multirotor cannot control the position and attitude simultaneously.

6. Conclusions and future

This paper presented a literature review of small-scale rotorcraft unmanned aerial robotic systems. The research state was introduced. Works on aerial manipulation of SRURSs were presented in three fashions. Mechanical structure design included three parts: i) grippers, ii) manipulators, and iii) cables and others. Modeling and control approaches were divided into two parts, independent and overall approaches including the simplified approach. Relative research groups and major achievements were presented in figures and tables for easy access. Problems, trends, and challenges were concluded and presented.

The overall approach is the trend of modeling approach, and increasingly more and more researchers are addressing SRURSs with manipulators. It can be forecasted that researchers will continue research on SRURSs with manipulators using the overall modeling approach in the future.

In fact, significant work remains to be undertaken in the future. This includes aerial manipulation of moving objects, anti-UAV combatting by aerial manipulation, and air-ground mobile cooperative manipulation. Furthermore, only a small number of industrial and commercial applications have been presented. There remains a significant amount of future research into aerial manipulation of small-scale rotorcraft unmanned aerial robotic systems.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 91748201 and 51505014).

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