Development of Bionic UAVs Cluster Technology

Ma Chunyao, *Feng Zhuoqun*, *Zheng Xiangming* *

College of Aerospace Engineering, Nanjing University of Aeronautics and
Astronautics, Nanjing 210016, P. R. China

(Received 20 March 2018; revised 20 April 2018; accepted 30 May 2018)

Abstract: With the wider use of UAV in various fields, the raising task complexity and the increasing environmental uncertainties, the higher requirements for UAV technology are put forward. The bionic UAV cluster system has the potential advantages of good stealth performance, strong environmental adaptability, wide expansion of task and high operational efficiency. It has excellent prospects in future information warfare, electronic warfare and conventional combat field. By reviewing the development of bionic UAV cluster technology, this paper summarizes and analyzes the latest research progresses of the key technologies such as aerodynamic mechanism and aerodynamic configuration design, driving mechanism design, autonomous flight control, adaptive networking and cluster control of bionic aircrafts.

Key words: bionic UAV; aerodynamic mechanism; structure design; ad-hoc networks; cluster control

CLC number: V19 **Document code**: A **Article ID**: 1005-1120(2018)S-0001-08

0 Introduction

Micro flapping wing aerial vehicle (MFAV) is a kind of bionic aircraft simulating the flight of birds and insects. It has the characteristics of small volume, light weight, low cost, good flexibility and strong stealth, which can be used in military and civilian field such as reconnaissance, collecting intelligence, and aerial photography. It is an important direction in the development of UAV.

As the task complexity and environmental uncertainty arising, a single UAV can no longer meet the increasing efficiency and quality requirements. More and more attention needs to be paid to the mutual cooperation of multiple UAVs to achieve group reconnaissance, combat for the future anti-terrorism, remote penetration, fighter escort and other combat missions.

The bionic multi-UAV system has the potential advantages of good stealth performance, strong environmental adaptability, wide task expansion and high operational efficiency. It has excellent prospect in future information warfare, electronic warfare and conventional combat. At present, the following key technologies exist in the development of bionic multiple UAV system:

(1) Flapping wing aerial vehicle(FAV) aerodynamic mechanism and configuration design.

(2) Flapping wing driving mechanism design.

(3) Bionic UAV autonomous flight control technology.

(4) Bionic multi-VAV adaptive networking technology.

(5) Bionic multi-UAV cluster control technology.

This paper summarizes the development of the above technologies in recent years.

1 Aerodynamic Mechanism and Configuration Design of Bionic Flapping Wings

1.1 Unsteady aerodynamics of bionic FAV

The sophisticated flapping movement is the

---

* Corresponding author, E-mail address: zhengxiangming@nuaa.edu.cn.

How to cite this article: Ma Chunyao, Feng Zhuoqun, Zheng Xiangming. Development of bionic UAVs cluster technology [J]. Trans. Nanjing Univ. Aero. Astro., 2018,35(S):1-8.
http://dx.doi.org/10.16356/j.1005-1120.2018.S.001

key to the efficient, flexible maneuvers of birds and insects. Since the early 20th century people began to study the aerodynamic characteristics of flapping wings, mainly based on the simplified model of quasi-steady assumption, using the lifting-line theory to analyze the lift-thrust generation mechanism. But it is not clear that whether the real mechanism of birds and insects' high lift and thrust lies in the "unsteady aerodynamic effects".

At present, the numerical aerodynamic research of the bionic flapping wing mainly focuses on the innovation and breakthrough of the unsteady CFD method under low Reynolds numbers. The difficulties and challenges are as follows:

(1) Flying organisms with different sizes and different types of fly in different ways. There are non-steady high-lift mechanisms waiting to be explored and found.

(2) The flexible structure of flying creatures plays an important role in flight and influences the aerodynamic performance greatly. At present, the aerodynamic research of flexible wing is still in the initial stage, and the coupling effect of fluid-structure needs further study.

(3) Boundary layer theory at low Reynolds number needs to be improved. How the boundary layers of flapping wings dynamically change and develop under low-Reynolds-number flow is a new topic and challenge in this area.

(4) The study of low-Reynolds-number unsteady flow is still insufficient. Calculation methods of low-Reynolds-number unsteady aerodynamics still face challenges in the discrete format, accuracy, dynamic grid processing, turbulence model and so on.

1.2 Aerodynamic configuration and mechanism of bionic flapping wing aircraft

According to the different imitated objects, some flapping wings are birds-shaped with gaps and valves, some are insect-like with high-frequency wings, and some are bat-like.

1.2.1 FAV imitating birds

The earliest FAV imitating birds can achieve relatively high-speed fly through the upward and downward motions of the wings cooperating with the empennage. Such FAVs are relatively easy to achieve and control, but usually cannot hover and take off or land vertically, and are generally larger in size, such as Microbat[1] and DelFly[2].

Birds can adjust the shape of wings. At present, in order to obtain the best aerodynamic characteristics, the study of aerodynamic configuration of birds-imitating flapping wings mainly adopts more sophisticated and complicated flutter mechanism based on the analysis of the aerodynamic mechanism of birds, adding asymmetrical movements and wing torsion along the wingspan into basic up and down flutter, such as Festo SmartBird[3], see Fig. 1.

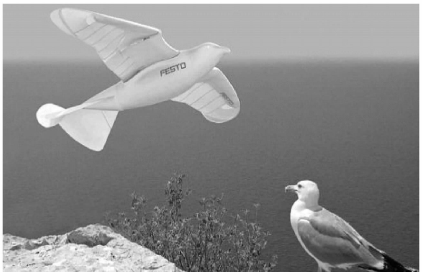

Fig. 1 SmartBird of Festo[3]

1.2.2 FAV imitating insect wings (or hummingbird)

Unlike birds, insects have very limited use of gliding. They can fly only through flapping wings in a high frequency to speed up the air. It is found that the insect lift obtained by quasi-steady theory is far from being able to overcome the gravity. At present, many scholars have explored the high-lift mechanism of insects [4-9].

By imitating the way insects flapping their wings and using the appropriate drive mechanism with flexible film wing, ornithopters can produce enough drag force to hover and to fly, like the U. S. Nano hummingbird[10] (see Fig. 2), Germany Festo's BiomicOpter, Korea Konkuk University imitation flapping wing aircraft and Harvard University of RoboFly [11].

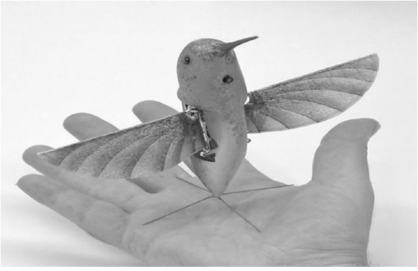

Fig. 2 Nano hummingbird[10]

2 Bionic Flapping Wing Driving Mechanism Design

The design of driving mechanism of flapping wings is one of the key factors to realize their flight. At present, the driving mechanism mainly includes the traditional mechanical drive, ionic polymer metal composite (IPMC) drive, piezoelectric drive, electrostatic drive, etc.

(1) Mechanical drive

The mechanical drive mechanism is the current mainstream and widely used in traditional flapping wing design because of its simple design and manufacturing process. It usually consists of motors, gears, cranks, rockers and so on. It is adopted in the design of nano hummingbird[10], "Bat Bot"[12], and Festo's smartbird[3]. In recent years, continuously variable transmission has been gradually applied to the bionic UAV, which can effectively lessen the number of motors, reduce the size of structure and improve the transmission efficiency[13].

(2) IPMC drive

IPMC is an ionic electroactive material, which is also known as "artificial muscle". It has characteristics of light weight, low driving voltage, large displacement, fast response, no noise, good flexibility and high energy density. Under the drive of a few volts, IPMC can reciprocate to achieve simple, effective and sophisticated motion control[14], which is suitable for flapping wings fluttering in high frequency[15-16].

(3) Piezoelectric drive

Piezoelectric materials can deform in an electric field, and can also generate an electric field when deforming. When placing the piezoelectric material in an alternating electric field[17], telescopic deformation can be produced as a power source to drive FAV[18]. Fig. 3 shows the structure of a piezoelectric driver.

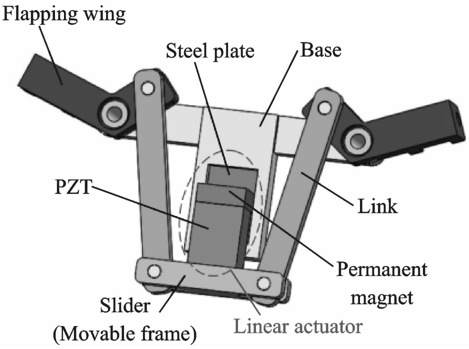

Fig. 3 Structure of piezoelectric driver

(4) Electrostatic drive

Electrostatic force is one of the most widely used driving forces in MEMs. In 2016, Liu et al. presented artificial electrostatic flapping wings using the "pivot-spar" brackets to achieve high lift force[19]. This micro driver makes the MAV lighter in mass.

Besides, there are electromagnetic material, chemical muscle and other driving methods.

3 Bionic UAV Autonomous Control

In the past two decades, many scholars have devoted themselves to the research of autonomous flight control technology of bird-imitating MFAV, and some typical research results are enumerated as follows.

In 2004, Na et al. applied the linear quadratic Gaussian (LQG) control method to the full state control of bird-imitating FAV[20]. The method uses the state feedback to realize the controller design, and observes the state variables that cannot be directly measured by the sliding state observer. However, the method requires detailed model information and assumes that the model parameters are available and accurate.

In 2006, Behal et al. applied the sliding mode adaptive control method to the full state control of bird-imitating aircraft with multi-layer flapping wing structure[21]. The method requires detailed model information, and assumes that the parameters are available and their values are accurate.

In 2010, Chung et al. used the heuristic control algorithm based on neurobiology to achieve the control of bird-like MAV, which requires all geometric and aerodynamic parameters of the aircraft to be measurable and accurate[22].

In 2012, Orlowski C T and Girard A R using the output feedback method based on accurate model to achieve the longitudinal channel flight control of bird-like micro-aircraft. The original strong coupling, highly nonlinear control system is simplified into a high-order linear model, though it has ignored a lot of non-linear factors[23].

In 2016, Armanini et al. used system identification methods to identify linear models from flight data and used the third order Fourier series to represent some time-varying parameters[24].

Besides, to FMAV suitable for complex environment and narrow space, the ability of autonomous obstacle avoidance is the key to flight safety and task performance. Except from detecting various of obstacles in the surroundings and making the real-time planning and implementation of obstacle-avoiding path correspondingly, the autonomous control system needs to ensure that the aircraft can carry out the traditional autonomous trajectory tracking and other tasks.

4 Adaptive Networking Technology of Bionic UAV Cluster

The basic idea of UAV Ad Hoc network is: communication of the multi-UAV system is not entirely dependent on ground control stations or satellite and other basic communication facilities, but see each UAV as a network node, and every node can forward instructions to each other, gather intelligence, exchange awareness of the situation and health state, and automatically connect to establish a wireless mobile network.

UAVs communication network mainly have the following layers: physical layer, medium access control (MAC) layer, network layer, transport layer, and their cross-layer interactions[25].

(1) Physical layer

In the physical layer, the data bits are modulated into sinusoidal waveforms and transmitted through the antenna to the air. Radio propagation models and antenna structures are investigated as the key factors that influence FANET physical layer design.

(2) MAC layer

Link quality changes and packet latency are two main design problems for FANET MAC layer design. Directional antenna and full-duplex radio circuits with multi-packet reception are some examples of promising technological advancements that can be used in FANET MAC layer[26].

(3) Network layer

One of the first flight experiments with FANET architecture was performed in SRI International. Shirani et al. developed a simulation framework to study the position-based routing protocols for FANETs[27]. Geographic position mobility oriented routing (GPMOR) was proposed for FANETs in Ref. [28].

(4) Transport layer

The success of FANET design is closely related to the reliability of the communication architecture, and setting up a reliable transport mechanism is essential, especially in a highly dynamic environment. The first FANET system operated on IP-based addressing performs poorly and is unsuited for FANETs. There are other emerging standard for messaging between unmanned systems, such as STANAG 4586[29].

(5) Cross-layer architectures

Cross-layer architectures are proposed to overcome the performance problems of layered architectures in the wireless environment which is widely used in the FANET. Cross-layer design can be defined as a protocol design by the violation of the layered communication architecture[30]. The adjacent layers can be designed as a super layer and interactions between non-adjacent layers can be supported. It is also possible to share protocol state information across all the layers to meet the specific requirements[31].

5 UAV Cluster Control Theory and Technology

5.1 Collaborative combat system structure

With the development of UAV cluster theory, the multi-UAV cooperative combat system has become a new research field. Taking a *n*-UAV system as an example, divide the *n* UAVs randomly into *i* groups as evenly as possible and select a UAV as the group leader from the group members. Members of each group constitute a distributed architecture, and the leaders constitute a distributed architecture as well. Cooperative combat system of UAV clusters is characterized by strong information exchange capacity, mutual coordination and self-decision-making ability.

5.2 Task assignment of UAV clusters

UAVs task assignment is to set a series of task scheduling such as combat power arrangements, weapons stowage, flight routes, target attack order, and cooperative air force arrangements to UAVs carrying out the mission.

From a functional view, task planning can be divided into task allocation and track planning.

5.2.1 Multi-UAV cooperative task allocation

Multi-UAV cooperative task allocation needs to consider the competition and cooperation between the UAVs, apart from considering the order in which a single UAV can complete its mission. According to different types of tasks need to be done by the multi-UAV system, task allocation can be divided into single task allocation and multiple task allocation.

(1) Multi-UAV single-task assignment

When UAVs work together to perform a single task, the problem is how to allocate the target sequence to different UAVs, which is mainly modeled as traveling salesman problem (TSP) and vehicle routing problem (VRP). The optimization algorithm to the solution mainly includes ant colony algorithm, genetic algorithm (GA), particle swarm optimization (PSO) and other algorithms.

(2) Multi-UAV multi-task assignment

When UAVs need to perform a variety of tasks, the problem is how to allocate goals and tasks for each UAV under the constraints of task timing, which is commonly modeled as multi-dimensional multi-selection backpack problem (MMKP) model, dynamic network flow optimization (DNFO) model, UAV cooperative multi-task allocation problem (CMTAP) model and mixed integer linear programming (MILP) problem model. MILP model can be a good coordination of time constraints. It is the most widely used model in multi-UAV task assignment researches.

5.2.2 Multi-UAV track planning

The main purpose of UAVs' track planning is to determine the optimal flight path for UAVs based on mission requirements and various constraints, while the spatial and temporal relationship between the multiple tracks is firstly needed to be coordinated. At present, many scholars try to use a variety of algorithms to solve this problem, such as UAV collaborative path planning method meeting timing constraints, multi-track planning method based on evolutionary algorithm or speed-adjusting strategy.

From a topological view, task planning can be divided into top-down planning and bottom-up planning[32].

Top-down planning is mainly based on hierarchical ideas. It can effectively reduce the difficulty of solving the problem, and has become the mainstream method[33]. Bottom-up planning is mainly based on the self-organization method, through the coordination between the underlying subsystems to achieve an overall organized state of the upper systems. It has a good self-adaptation towards environmental and task changes[34].

5.3 UAV cluster formation control

5.3.1 Formation control method

At present, there are three main control methods for UAV formation control: leader-follower method, virtual navigation method and behavior control method.

(1) Leader-follower method

leader-follower is the most commonly used method for UAVs formation control[35]. Select a UAV in the formation as a leader to maintain the main flight path, and other UAVs follow the leader with some control strategies. This method is direct and easy to understand, but it has the problem conducting errors. Once the leader is disturbed, the entire formation will be affected.

(2) Virtual pilot method

Virtual pilot method sees the formation as a single virtual rigid body, and set a virtual geometric center according to which movements of UAVs happen. This method is easy to conduct error and has a good accuracy. However, because it is a centralized method, the reliability is relatively poor, and collision among the UAVs is likely to occur. In November 2014, a research team of the University of West Virginia successfully achieved a formation flight of three YF22 UAVs in the virtual pilot way.

(3) Behavior-based method

Behavior-based control method is a distributed method. Each of the subsystem in the formation is given several basic control behaviors, such as formation, collision avoidance, etc. The behavior of the overall system can be considered as the weighted average of the behaviors of all subsystems. This method has good abilities in adaptation and collision avoiding. However, behaviors of subsystems are difficult to define and design.

5.3.2 Formation control algorithm

Given the initial state of a UAV system and the relative state of the system, the continuous inputs of each flight unit are piecewise linear by a control parameterization and time discretization method. The approximation piecewise linearization control inputs are used to substitute for the continuous inputs. In this way, the multi-UAV formation reconfiguration problem can be formulated as an optimal control problem with dynamical and algebraic constraints. In recent years, the commonly used formation control methods include the annealing algorithm, PSO[36], backstepping algorithm, GA[37], ant colony algorithm[38], etc.

6 Conclusions

The bionic UAV cluster system is an inevitable direction of researches for aerotechnics. Breakthroughs have been made respectively in related areas such as bionic UAV design, UAVs formation control, cluster control theory, etc. But to make a perfect fusion of the bionic UAV and cluster control theory is a new research area which has yet to be explored systematically. This paper analyses and summarizes the contents and development situation of key technologies of bionic UAV cluster system to offer a reference for bionic UAV cluster system design.

References:

[1] PORNSIN-SIRIRAK T N. Microbat : A palm-sized electrically powered ornithopter[J]. Proceedings of the Nasa/jpl Workshop on Biomorphic Robotics, 2001.

[2] CROON G C H E D, CLERCQ K M E D, RUIJSINK, et al. Design, aerodynamics, and vision-based control of the DelFly[J]. International Journal of Micro Air Vehicles, 2009, 1(2):71-97.

[3] MACKENZIE D. A flapping of wings[J]. Science, 2012, 335(6075):1430.

[4] ELLINGTON C P. The aerodynamics of hovering insect flight. IV. Aeorodynamic mechanisms[J]. Philosophical Transactions of the Royal Society of London, 1984, 305(1122):145-181.

[5] WEISFOGH T. Quick estimates of flight fitness in hovering animals, including novel mechanisms for lift production[J]. Journal of Experimental Biology, 1973, 59(1):169-230.

[6] LIGHTHILL M J. On the Weis-Fogh mechanism of lift generation[J]. Journal of Fluid Mechanics, 2006, 60(1):1-17.

[7] MAXWORTHY T. Experiments on the Weis-Fogh mechanism of lift generation by insects in hovering flight. Part 1. Dynamics of the 'fling'[J]. Journal of Fluid Mechanics, 1979, 93(1): 47-63.

[8] ELLINGTON C P, VAN DEN BERG C, WILLMOTT A P, et al. Leading-edge vortices in insect flight[J]. Nature, 1996, 384(6610): 626.

[9] BIRCH J M, DICKINSON M H. Spanwise flow and

the attachment of the leading-edge vortex on insect wings[J]. Nature, 2001, 412(6848): 729.

[10] KEENNON M, KLINGEBIEL K, WON H, et al. Development of the nano hummingbird: A tailless flapping wing micro air vehicle[C]//AIAA aerospace sciences meeting. Reston, VA: AIAA, 2012: 1-24.

[11] LAUDER G V. Flight of the robofly[J]. Nature, 2001, 412(16): 688-689.

[12] RAMEZANI A, SHI X, CHUNG S J, et al. Bat Bot (B2), a biologically inspired flying machine[C]// IEEE International Conference on Robotics and Automation. [S. l.]: IEEE, 2016:3219-3226.

[13] CHUANG J C. Variable speed flapping wing micro air vehicle using a continuous variable transmission design[D]. Dayton, OH : Wright State University, 2014.

[14] KIM K J, SHAHINPOOR M. Effect of the surface-electrode resistance on the actuation of ionic polymer-metal composite (IPMC) artificial muscles[J]. Proceedings of SPIE, 1999, 3669:308-319.

[15] MUKHERJEE S, GANGULI R. Ionic polymer metal composite flapping actuator mimicking dragonflies [J]. Computers, Materials and Continua, 2010, 19 (2):105-133.

[16] JAYABALAN S S, GANGULI R, MADRAS G. Nanomaterial-based ionic polymer metal composite insect scale flapping wing actuators[J]. Mechanics of Composite Materials & Structures, 2016, 23(11): 1300-1311.

[17] STELTZ E, SEEMAN M, AVADHANULA S, et al. Power electronics design choice for piezoelectric microrobots[C]// IEEE/RSJ International Conference on Intelligent Robots and Systems. [S. l.]: IEEE, 2007:1322-1328.

[18] PENG Y, CAO J, LIU L, et al. A piezo-driven flapping wing mechanism for micro air vehicles[J]. Microsystem Technologies, 2017, 23(4):967-973.

[19] LIU Z, YAN X, QI M, et al. Electrostatic flapping wings with pivot-spar brackets for high lift force [C]// IEEE, International Conference on MICRO Electro Mechanical Systems. [S. l.]: IEEE, 2016: 1133-1136.

[20] NA S, LIBRESCU L, MARZOCCA P, et al. Aeroelastic response of flapped wing systems using robust estimation methodology[J]. Journal of Guidance, Control, and Dynamics, 2006,29(1):199-202.

[21] BEHAL A, RAO V M, MARZOCCA P, et al. Adaptive control for a nonlinear wing section with multiple flaps[J]. Journal of Guidance Control & Dynamics, 2006, 29(3):744-749.

[22] DOROTHY M, CHUNG S J. Methodological remarks on CPG-based control of flapping flight[C]// AIAA Atmosphere Flight Mechanics Conference. Toronto, Ontario Canada: AIAA, 2010.

[23] ORLOWSKI C T, GIRARD A R. Longitudinal flight dynamics of flapping-wing micro air vehicles[J]. Journal of Guidance Control & Dynamics, 2012, 35 (4):1115-1131.

[24] ARMANINI S F, DE VISSER C C, DE CROON G C H E, et al. Time-varying model identification of flapping-wing vehicle dynamics using flight data[J]. Journal of Guidance Control & Dynamics, 2016, 39 (3):526-541.

[25] BEKMEZCI I, SAHINGOZ O K, TEMEL S. Flying Ad-Hoc networks (FANETs): A survey[J]. Ad Hoc Networks, 2013, 11(3): 1254-1270.

[26] CHOI J I, JAIN M, SRINIVASAN K, et al. Achieving single channel, full duplex wireless communication[C]//International Conference on Mobile Computing and Networking, MOBICOM 2010. Chicage, Illinois, USA: ACM, 2010: 1-12.

[27] SHIRANI R, ST-HILAIRE M, KUNZ T, et al. The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks[C]//Communication Networks and Services Research Conference (CNSR), 2011 Ninth Annual. [S. l.]: IEEE, 2011: 161-166.

[28] LIN L, SUN Q, LI J, et al. A novel geographic position mobility oriented routing strategy for UAVs [J]. Journal of Computational Information Systems, 2012, 8(2): 709-716.

[29] North Atlantic Treaty Organization. NATO allies to ratify major agreement on interoperability of unmanned air vehicles (UAVs) [EB/OL]. https://www. nato. int/docu/pr/2002/p02-106e. htm, 2002-09-16.

[30] FOUKALAS F, GAZIS V, ALONISTIOTI N. Cross-layer design proposals for wireless mobile networks: A survey and taxonomy[J]. Communications Surveys & Tutorials IEEE, 2008, 10(1):70-85.

[31] JARUPAN B, EKICI E. A survey of cross-layer design for VANETs[J]. Ad Hoc Networks, 2011, 9 (5): 966-983.

[32] OLLERO A, KONDAK K. 10 years in the cooperation of unmanned aerial systems[C]//Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on. [S. l.]: IEEE, 2012: 5450-5451.

[33] WONG E M, BOURGAULT F, FURUKAWA T. Multi-vehicle Bayesian Search for Multiple Lost Targets[C]// IEEE International Conference on Robotics and Automation. [S. l.]: IEEE, 2005: 3169-3174.

[34] CASBEER D W, BEARD R. Distributed information filtering using consensus filters[C]// Conference on American Control Conference. [S. l.]: IEEE Press, 2009:1882-1887.

[35] XU Y, ZHEN Z. Multivariable adaptive distributed leader-follower flight control for multiple UAVs formation[J]. Aeronautical Journal -New Series-, 2017, 121(1241):1-24.

[36] ZHANG M. PSO & PID controller design of UAV formation flight [C]// Guidance, Navigation and Control Conference. [S. l.]: IEEE, 2017:592-596.

[37] DUAN H, LUO Q, SHI Y, et al. Hybrid particle swarm optimization and genetic algorithm for multi-UAV formation reconfiguration[J]. IEEE Computational Intelligence Magazine, 2013, 8(3):16-27.

[38] LI T, JIANG J, ZHEN Z, et al. Mission planning for multiple UAVs based on ant colony optimization and improved Dubins path[C]// Guidance, Navigation and Control Conference. [S. l.]: IEEE, 2017: 954-959.

Ms. **Ma Chunyao** received her Bachelor's degree from Nanjing University of Aeronautics and Astronautics, Nanjing, China, 2017. She is currently a Ph. D. Student at Nanyang Technological University. Her research focuses on UAV design, UAV cluster control and air traffic management.

Mr. **Feng Zhuoqun** received Bachelor's degree in Shenyang Aerospace University in 2015. He is now studying at Nanjing University of Aeronautics and Astronautics. His research is focused on flight vehicle collectivity design.

Dr. **Zheng Xiangming** received his Ph. D. degree in aircraft design and engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, 2008. He is currently a full associate professor at NUAA. His research focuses on UAV design and UAV control.

(Production Editor: Sun Jing)