To cite this article: ZHAO R, XU J, XIANG X B, et al. A review of path planning and cooperative control for MAUV systems[J/ OL]. Chinese Journal of Ship Research, 2018, 13(6). http://www.ship-research.com/EN/Y2018/V13/I6/58. DOI:10.19693/j.issn.1673-3185.01028

## A review of path planning and cooperative control for MAUV systems

ZHAO Rui<sup>1</sup>, XU Jian<sup>1</sup>, XIANG Xianbo<sup>2</sup>, XU Guohua<sup>2</sup>

1 China Ship Development and Design Center, Wuhan 430064, China

2 School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology,

Wuhan 430074, China

**Abstract:** The Autonomous Underwater Vehicle (AUV) is an important tool for ocean exploration and the exploitation of underwater resources, which plays important roles in civilian and military fields. Along with the research progress of AUVs, it has become the current development trend to cooperate on completing underwater operations by constructing the Multiple Autonomous Underwater Vehicle (MAUV) system. The MAUV system has important theoretical research significance and practical value for improving the intelligence level of underwater vehicles and developing marine equipment. In this paper, the state of the art of the MAUV is presented from the point of view of practical application and scientific research. The main methods of path planning and cooperative control for MAUV are illustrated, including artificial intelligence and formation control techniques. Finally, the research trends of MAUV are also discussed and the main topic is highlighted.

Key words: Multiple Autonomous Underwater Vehicle (MAUV) systems; path planning; flocking cooperation; formation control

**CLC number:** U674.941

## **0** Introduction

As a kind of underwater vehicle without cables, the Autonomous Underwater Vehicle (AUV) is an important tool for the exploration and development of marine resources.

AUV is widely used in the military field, such as anti-submarine warfare, mine warfare, intelligence reconnaissance, patrol and surveillance, logistics support, topographic mapping, and underwater construction <sup>[1-3]</sup>. Therefore, all countries in the world are devoting themselves to the research of advanced AUV systems to enhance national defense. Many research institutes such as the Woods Hole Oceanographic Institution, the Monterey Bay Aquarium Research Institute and the Ocean Research Center for Massachusetts Institute of Technology in the United States have developed a large number of AUVs for short-term and long-term mine reconnaissance systems. In 1990, the Norwegian Defense Research Establishment formulated a long-term development plan for AUV, in which the HUGIN series AUV has been used in the mine-hunting demonstration experiments of Royal Norwegian Navy. At the same time, France and Russia have also carried out a lot of research work on military AUV<sup>[4]</sup>.

In the civilian field, AUV is mainly used for marine environmental investigation, seabed mineral and biological resources exploration, marine rescue, marine archaeology, and construction and maintenance of submarine cable<sup>[5]</sup>. With the support of China Ocean Mineral Resources R&D Association, China

XIANG Xianbo, male, born in 1978, Ph.D., associate professor, doctoral supervisor. Research inter-

st: control technology of marine vehicle. E-mail: xbxiang@hust.edu.cr

Received: 2017 - 06 - 19

Supported by: National Natural Science Foundation of China (51579111); Research Foundation of State Key Laboratory of Ocean Engineering (201504)

Author(s): ZHAO Rui (Corresponding author), female, born in 1981, master, senior engineer. Research interest: overall and control technology of autonomous underwater vehicle (AUV). E-mail: zhaorui701s@163.com

XU Jian, male, born in 1963, Ph.D., professor, doctoral supervisor. Research interest: overall research and design of ships.

and Russia jointly developed the CR-01 and CR-02 (6 000 m) AUVs, which can be used to perform acoustic, optical and hydrological measurement tasks in the polymetallic nodule mining areas of deep-sea flat terrain. The US Tesla Offshore has carried out the marine pipeline maintenance services and the mapping of seabed geographical environment by using Bluefin-21 AUV. In 2011, the Monterey Bay Aquarium Research Institute in the United States launched the "Dorado AUV" in the Juan de Fuca Ridge. The lowest navigation altitude of the AUV is 50 m above the seabed, and its multi-beam sonar can accurately map the seabed topography around the crater <sup>[6-7]</sup>.

In recent decades, in view of the importance of AUV in civilian and military fields, countries have made considerable progress in AUV technology <sup>[8-10]</sup>, and have developed the Multiple Autonomous Underwater Vehicle (MAUV) system based on mission requirements.

## 1 MAUV system

### **1.1** Progress in application research

Along with the research progress of AUVs, they have become the underwater autonomous operating system of performing specified tasks. However, it is difficult for a single AUV to meet the application requirements of some dynamic and complex tasks, resulting in the generation of MAUV system <sup>[11-13]</sup>. In terms of underwater operation, MAUV system has incomparable advantages compared with a single AUV system because of its spatial distribution, high efficiency, robustness and flexibility. The core idea of MAUV system is to form a system with multiple simple AUVs to accomplish a given task by controlling the coordination and cooperation of each AUV [14 - 17]. Currently, the US Space and Naval Warfare Systems Center has designed a distributed MAUV underwater monitoring system, and established an underwater base station to monitor underwater data. On the basis of intelligent MAUV system, the Deep Sea Engineering and Technology Research Center of Harbin Engineering University has also carried out research on submarine combat environment detection and underwater transportation of large-scale goods [18]. The underwater network composed of MAUV can be combined with the water network to form an omni-directional and three-dimensional information network, in which surface warships or buoys can be used as relay nodes to connect water and underwater. Because

the underwater information network can be used for sea area surveillance, intelligence gathering and environmental monitoring in complex or high-risk environments for a long time <sup>[19-22]</sup>, the MAUV system has important research significance and application value.

### **1.2** Progress in scientific research

In order to ensure the smooth completion of various cooperative control tasks by MAUV, such as three-dimensional collaborative investigation of underwater environment, underwater cooperative search, underwater cooperative capture and underwater information transmission, it is first necessary to clarify the path planning of each AUV in the MAUV cooperative operation system. However, the MAUV cooperative path planning is a large-scale combinatorial optimization problem with complex constraints. It is necessary to plan the optimal or near-optimal path from the starting point to the end point for each AUV in the system, and then optimize the composite paths of the whole system through coordination and combination strategy, further achieving the shortest total consumption time of system, minimum energy consumption, minimum turning radius and maximum acceleration [23-25].

On the other hand, when a certain task is completed through MAUV flocking cooperation, it is generally required that multiple AUVs maintain a certain formation to perform tasks, namely that the relative spatial distance between the AUV and other AUVs in the group should be controlled during the navigation to realize the formation control of AUV cluster. Multiple AUVs in the system will transit from a random initial state to a stable state that is regular or meets the design requirements. In the process of moving, the MAUV cluster not only follows certain formation constraints, but also adapts to the current working environment (for example, physical constraints of obstacles or space), which is quite challenging.

## 2 Path planning of MAUV

SU

n

1

At present, the path planning methods of MAUV are mainly as follows.

1) Bio-inspired Self-Organizing Map (SOM) algorithm.

The bio-inspired SOM algorithm consists of three steps: First, the winning neurons are selected by calculating the Euclidean distance. Secondly, after a certain neuron wins, a neighborhood function is de-

-researc

signed, which determines the influence of input neurons on winning neurons and neighboring neurons. The winning neurons are most affected; the influence on neighboring neurons is gradually reduced; and the neurons outside the neighborhood are not affected. The influence determines the weight adjustment of neighboring neurons in a certain iteration process. Finally, the AUV reaches the target point by updating the three-dimensional weight vector method <sup>[26]</sup>.

2) Ant colony algorithm.

The ant colony algorithm is proposed by Dorigo, an Italian scholar. Optimization is realized through this algorithm by simulating the division and cooperation of ant society [27]. The MAUV cooperative path planning based on ant colony algorithm includes path optimization and path checking. Before path optimization, the number of path points to be accessed by each AUV should be allocated. In order to ensure that the tasks of each AUV are equal, the access path points should be allocated as evenly as possible. The order in which each path point is accessed is realized by the ant colony algorithm, in which the starting point of a certain AUV, the allocated path point and its end point are connected to form the path of the AUV. The same operation can be performed on all AUVs to generate the path of MAUV. If the number *n* of path points can be exactly divided by the number *m* of AUVs, *n/m* path points will be allocated for each AUV. If n cannot be divided by m, the remainder will be assigned to each AUV one by one from the beginning to the end until the allocation is completed. The length of the path can be obtained by calculating the distance between all neighboring path points in the path (including the starting point and the end point of the AUV), and the total distance of MAUV can be obtained by summing the path length of each AUV  $^{\scriptscriptstyle [28-29]}$ 

3) Internal Spiral Coverage (ISC) algorithm.

The ISC algorithm is an online coverage algorithm based on raster map <sup>[30]</sup>. In this algorithm, a simple circular robot is adopted to cover the environment, and the range sensor (odometer) inside the robot is assumed to be able to accurately measure the global coordinates of the robot. In the coverage process, ISC algorithm is divided into two stages: the boundary exploration stage and the online coverage stage. In the boundary exploration stage, the robot starts from any vertex of the environment and moves in a circle along the boundary of environment on the right side. The grid of contact sensor on the right side of the robot is assigned the value of **0**, indicating that the grid

1

wnioaded

cannot be covered. The grid passed by the robot is assigned the value of 1, which means that the grid has been covered. And the grid on the left side of the robot is assigned the value of 2, indicating the grid to be covered in the next circle, namely, the coverage path of online planning. At the end of the boundary exploration stage, the environmental boundary can be obtained. At this time, the robot completes a circle of coverage near the boundary, and plans the motion path of the next circle. Then, it enters the online coverage stage. In the online coverage stage, the robot moves along the continuous grid assigned the value of 2 in the boundary exploration stage, and then the grid is assigned the value of 1. At the same time, the unassigned grid on the left side of the robot is assigned the value of 2. When the second circle of coverage is finished, the coverage path of the third circle can be generated. In this way, the robot spirals inwards to cover all areas. If there is an obstacle inside the environment, the obstacle will block the planned path, resulting in discontinuity of the grid assigned the value of 2. However, the obstacle will be detected by the contact sensor in front of the robot during the next circle of coverage. The robot will still move around the obstacle by walking along the boundary of the object on the right side, and it will return to the original planning path and continue to cover until the grid assigned the value of 2 appears again. For the common single rectangular environment, the environmental boundary is inwardly spiraled to complete coverage through this algorithm [31-33].

4) Particle Swarm Optimization (PSO) algorithm.

In 1995, Kennedy and Eberhart proposed the PSO algorithm. In the PSO algorithm, a group of random particles should be initialized, and then these random particles will follow the current optimal particles to search in the solution space, namely that the optimal solution is obtained through iteration <sup>[34]</sup>. According to the PSO algorithm, Li et al. <sup>[35]</sup> proposed a MAUV cooperative path planning algorithm with parallel two-layer structure. The algorithm is divided into two layers: the main layer and the sub-layer. The primary task of sub-layer planning is to plan paths separately for each AUV through PSO algorithm. Since the starting point, end point and environment of each AUV in the system are different, the optimal path for each AUV will be eventually different. The main task of the main layer planning is to make the best combination of different AUV paths, so that the overall cooperative paths of multiple AUVs in the combination are optimal and have no collision with

w.snib-researc

each other. In the process of sub-layer planning, with the increase of iterations, there will be problems such as local optimum and slow convergence in the later stage for the standard PSO algorithm. In order to solve these problems, firstly, the inertia weighting factor w and the learning factors c1 and c2 in the PSO algorithm are dynamically adjusted by adaptive parameters, and the appropriate evaluation function for path planning is selected to obtain the optimal path of each AUV. And then, the MAUV cooperative optimal path of the whole system should be calculated by using the main layer planning combined with Differential Evolution (DE) algorithm, namely that the combined optimal path without collision among multiple AUVs (between AUV and obstacles, and among AUVs) and with minimal system consumption can be obtained through the variation, crossover and selection of DE algorithm. Finally, the adaptive function is evaluated [36].

## 3 MAUV flocking cooperation technology

When performing tasks, each AUV in the MAUV formation should maintain a certain formation and a certain space distance from other AUVs in the formation. In terms of MAUV formation control, the formation control methods of mobile robots and surface ships can be referred to, such as the method based on leader-follower, the behavior and the virtual structure <sup>[37-38]</sup>, shown as follows.

1) Behavior-based method.

The behavior-based control method generates the desired overall behavior by designing the basic behavior and local control rules of robots. The formation controller consists of a series of behaviors, and each robot has basic behaviors, each of which has its own target or task. In general, the behavior of robots includes collision avoidance, obstacle avoidance, moving towards the target and maintaining the formation. The collision avoidance means that the collision among robots is avoided during the movement, and the obstacle avoidance means that formation robots avoid encountering obstacles in the dynamic environment. Maintaining the formation is the most basic independent behavior in formation control [39], and moving towards the target is to achieve the pre-specified state. Balch and Arkin first proposed a behavior-based control method, and designed the behavior controller of maintaining the formation by using two circular strategies. Cao et al. [40] proposed a control implementation method for weighted synthesis of sub-behaviors, namely that the control variables of each sub-behavior are calculated separately, and then the integrated control variables are obtained by weighted averaging.

2) Artificial potential field method.

In terms of the artificial potential field method, constraints among robots in the environment and formation are represented by designing the artificial potential field and the potential field function, and the potential field is constructed through the obstacle repulsion force and the target point gravitational force of robots. The analysis and control are conducted based on this, and the robot will choose the direction of motion from the minimum potential valley obtained in the plane. The advantages of this method are that it is simple and easy to control in real time; especially, it can deal with obstacle avoidance and collision avoidance of obstacle constraints effectively. The disadvantage is that the potential field function is difficult to be designed and there is a local extremum problem. Liang et al. [41] proposed a distributed controller based on the potential field function for the nonholonomic mobile robots in the obstacle environment. This distributed controller can ensure that formation robots achieve the preset formation, while avoiding collisions with each other and with obstacles [42].

3) Leader-follower method.

In terms of the leader-follower method, a certain robot is designated as the leader in the MAUV formation, and the rest are followers. The followers will track the position and direction of the robot leader at a certain interval <sup>[43-44]</sup>. In this method, one or more leaders can be designated, but only leaders of a group formation can be specified. The leader-follower method has two types of controllers: l-l controller and  $l-\psi$  controller. The relative position among three robots is considered in 1-1 controller. Once the distance between the follower and two leaders reaches the set value, the whole formation can be considered to be stable. The goal of  $l - \psi$  controller is to make the distance and relative angle between the follower and the leader reach the set value <sup>[45]</sup>. Through the leader-follower formation control method, the formation control problem of underwater robots can be transformed into that of follower tracking the position and course of the leader through the hydrophone. Considering the communication or mechanical failure of a robot in the MAUV formation, a formation fault-tolerant control algorithm is established, which can automatically re-adjust the formation after the

w.snid-research.com

robot fails, avoiding the subsequent robots dropping out, thus realizing the fault-tolerant control of the formation <sup>[46-47]</sup>.

4) Virtual structure method.

The virtual structure method is mainly applied to the formation flight control of aircraft and artificial satellite. In this method, robots can maintain a certain geometric shape with other robots, and the rigid structure thus formed is called a virtual structure. Although the position of each robot relative to the reference system remains unchanged, it can change its direction according to a certain degree of freedom. A certain formation can be formed through MAUV by using different reference points on the rigid structure as their respective tracking targets: First, the desired dynamic characteristics of virtual structure should be defined. And then, the motion of virtual structure is transformed into the desired motion of each robot. Finally, the trajectory tracking control method of robots is obtained [48-50].

5) Model Predictive Control (MPC) method.

Traditional control methods are generally applicable to control with clear models and deterministic environments, but the environment in practical applications is generally dynamic and uncertain <sup>[51]</sup>. Based on the change of dynamic environment and the uncertainty in the process, MPC method repeatedly uses finite optimization results instead of global optimization results to realize the ideal combination of optimization and feedback and the full utilization of information. Through online rolling optimization combined with feedback correction of real-time information, optimization at every moment can be carried out based on the actual process <sup>[52]</sup>.

## **4** Research prospects

The MAUV system has far-reaching political, economic and strategic significance to enhance the detection ability of marine resources and improve the defensive ability of marine territory in China<sup>[53-54]</sup>. At present, in terms of the path planning and cooperative control for MAUV systems, there are mainly following research difficulties, which are also the development direction of follow-up research.

1) MAUV dynamic adaptive technology.

102

wn

After obtaining the uncertain model of marine environment, we should study how to obtain the overall optimal performance of underwater vehicle cluster network through dynamic adaptive formation. The main research contents include the limited communication in water, the asynchronous\_transmission of in-

 $\mathbf{n} \mathbf{e} \mathbf{c}$ 

formation among the individual vehicles in formation, the adaptive control of MAUV formation network, the analysis of the overall performance of MAUV formation system, and the research of path planning method for underwater vehicle under optimal control<sup>[55-56]</sup>.

In the course of navigation, with the reference path of global route of offline planning, the path planning in the horizontal direction and the vertical direction can be carried out respectively, and the objective function of online planning can be established. Taking the linearized lateral motion equation of an underwater vehicle as the equality constraint, the Hamilton function is constructed through the minimum principle to solve optimal path and achieve the optimal control of path. At the same time, it is solved through the differential equations of classical variational extremum conditions combined with the gradient iteration method and the one-dimensional initial value search method. And then, more accurate and feasible three-dimensional underwater path can be obtained.

2) MAUV distributed control technology.

There are certain similarities between MAUV formation control and cooperative control of multi-agents in the field of artificial intelligence. Multi-agent cooperative control technology can realize the functions of fast cluster control [57], traction control [58], target capture [59-61], formation movement along a given path [62] and formation control under delay constraint <sup>[63]</sup>. Therefore, how to regard a single vehicle as a relatively independent agent and draw lessons from the existing agent cooperative control method to achieve MAUV cluster formation control is of great significance for the research. It is noteworthy that the cooperative mechanism of multi-agent system is closely related to the group architecture, individual architecture, perception, communication and learning of the system [64-65].

In order to solve the distributed control problem, it is necessary to study how to complete their sub-tasks independently to achieve mutual cooperation by using agents, and pay attention to how to coordinate their respective knowledge, goals, skills and plans among multiple agents to take joint action to solve the problem. While carrying out distributed control of the MAUV cluster, it can be equipped with mission sensors and various acoustic devices (for example, multibeam echo sounder, side-scan sonar, CTD, ultra-short baseline positioning system, Doppler speed log and underwater sound communication

w.snin-research.com

systems) to quickly and efficiently complete the established tasks [66-67]. Therefore, based on distributed control technology, MAUV group behavior control and cooperative decision-making and management of multiple vehicles can be realized, and then the cooperative task is completed.

#### 5 Conclusions

At present, MAUV system is an important development direction of underwater vehicle technology. Through cooperation and coordination among robots, MAUV system can not only improve the basic functions of each robot, but also further expand intelligent behavior in robot interaction. And then, cooperative tasks, such as three-dimensional collaborative investigation of underwater environment, underwater cooperative search, underwater cooperative capture and underwater information transmission, can be accomplished, which are conducive to improve the intelligence level of underwater vehicles and develop marine equipment.

In this paper, in terms of the path planning and cooperative control of MAUV system, its practical application, scientific research progress and key technologies are systematically combed and summarized, and the subsequent research directions are discussed.

## References

- $\begin{bmatrix} 1 \end{bmatrix}$ XU Y R, SU Y M, PANG Y J. Expectation of the development in the technology on ocean space intelligent unmanned vehicles [J]. Chinese Journal of Ship Research, 2006, 1(3): 1-4 (in Chinese).
- [2] SIMPKINS C A. Introduction to autonomous manipulation: case study with an underwater robot, SAUVIM [J]. IEEE Robotics and Automation Magazine, 2014, 21(4): 109-110.
- [3] XIANG X B. Research on path following and coordinated control for second-order nonholonomic AUVs [D]. Wuhan: Huazhong University of Science and Technology, 2010 (in Chinese).
- [4] DIERCKS A R, WOOLSEY M, JARNAGIN R, et al. Site reconnaissance surveys for oil spill research using deep-sea AUVs[C]//Proceedings of 2013 Oceans-San Diego. San Diego, CA: IEEE, 2013: 1-5.
- WERNLI R L. AUV commercialization-who's leading [5] the pack [C]//Proceedings of Oceans 2000 MTS/IEEE Conference and Exhibition. Providence, Rhode Island: IEEE, 2000: 391-395.
- KENNEDY J, EBERHART R. Particle swarm optimi-[6] zation [C]//Proceedings of IEEE International Conference on Neural Networks. Perth, Australia: IEEE, 1995: 1942-1948.

- [7] EBERHART R, KENNEDY J. A new optimizer using particle swarm theory [C]//Proceedings of the 6th International Symposium on Micro Machine and Human Science. Nagoya, Japan: IEEE, 1995: 39-43.
- XIANG X B, JOUVENCEL B, PARODI O. Coordinat-[8] ed formation control of multiple autonomous underwater vehicles for pipeline inspection [J]. International Journal of Advanced Robotic Systems, 2010, 7(1): 75-84.
- [9] OSTAFICHUK P M. AUV hydrodynamics and modelling for improved control[D]. Canada: The University of British Columbia, 2004.
- [10] ANTONELLI G. Underwater robots [M]. 3rd ed. Berlin: Springer, 2013.
- $\begin{bmatrix} 11 \end{bmatrix}$ HEALEY A J. Application of formation control for multi-vehicle robotic minesweeping [C]//Proceedings of the 40th IEEE Conference on Decision and Control. Orlando, USA: IEEE, 2001: 1497-1502.
- ZHAO R, XIANG X B, YU C Y, et al. Coordinated [12] formation control of autonomous underwater vehicles based on leader-follower strategy [C]//Proceedings of Oceans 2016 MTS/IEEE Monterey. Monterey, USA: IEEE, 2016: 1-5.
- [13] JIANG D P. Research on coordinated control technology for multiple autonomous underwater vehicles [D]. Harbin: Harbin Engineering University, 2011 (in Chinese).
- [14] KOO T J, LI R Q, QUOTTRUP M M, et al. A framework for multi-robot motion planning from temporal logic specifications [J]. Science China Information Sciences, 2012, 55(7): 1675-1692.
- [15] WOITHE H C, KREMER U. Trilobite G: a programming architecture for autonomous underwater vehicles [J]. ACM SIGPLAN Notices, 2015, 50(5): 14.
- [16] CUI R X, YAN W S, XU D M. Synchronization of multiple autonomous underwater vehicles without velocity measurements [J]. Science China Information Sciences, 2012, 55(7): 1693-1703.
- [17] PAULL L, SAEEDI S, SETO M, et al. AUV navigation and localization: a review [J]. IEEE Journal of Oceanic Engineering, 2014, 39(1): 131-149.
- MATSUDA T, MAKI T, SAKAMAKI T, et al. Perfor-[18] mance analysis on a navigation method of multiple AUVs for wide area survey [J]. Marine Technology Society Journal, 2012, 46(2): 45-55.
- [19] GKIKOPOULI A, NIKOLAKOPOULOS G, MANE-SIS S. A survey on underwater wireless sensor networks and applications [C]//Proceedings of the 20th Mediterranean Conference on Control and Automation. Barcelona, Spain: IEEE, 2012: 1147-1154.
- [20] AKYILDIZ I F, WANG P, LIN S C. Softwater: software-defined networking for next-generation underwater communication systems [J]. Ad Hoc Networks, 2016, 46: 1-11.
- YOON S, AZAD A K, OH H, et al. AURP: an 21 AUV-aided underwater routing protocol for underwater acoustic sensor networks [J]. Sensors, 2012, 12 downloaded from www

-SN

-researcn.com

(2): 1827-1845.

- [22] SUN Y, ZHANG R. Research on global path planning for AUV based on GA [M]//ZHAGN T B. Mechanical Engineering and Technology. Berlin: Springer, 2012: 311-318.
- [23] WANG G. The research of path planning based on ELM for AUV [D]. Qingdao: Ocean University of China, 2013 (in Chinese).
- [24] HUANG H, ZHU D Q, DING F. Dynamic task assignment and path planning for multi-AUV system in variable ocean current environment[J]. Journal of Intelligent and Robotic Systems, 2014, 74 (3/4) : 999-1012.
- [25] ZHU D Q, HUANG H, YANG S X. Dynamic task assignment and path planning of multi-AUV system based on an improved self-organizing map and velocity synthesis method in three-dimensional underwater workspace [J]. IEEE Transactions on Cybernetics, 2013, 43(2): 504-514.
- [26] MANINGO J M Z, FAELDEN G E U, NAKANO R C S, et al. Obstacle avoidance for quadrotor swarm using artificial neural network self-organizing map[C]// Proceedings of 2015 International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management. Cebu City, Philippines: IEEE, 2015: 1-7.
- [27] SUTANTYO D, LEVI P, MÖSLINGER C, et al. Collective-adaptive Lévy flight for underwater multi-robot exploration [C]//Proceedings of 2013 IEEE International Conference on Mechatronics and Automation. Takamatsu, Japan: IEEE, 2013: 456-462.
- [28] HUANG Q, ZHENG G L. Route optimization for autonomous container truck based on rolling window[J]. International Journal of Advanced Robotic Systems, 2016, 13(3): 112.
- [29] LIU J H, YANG J G, LIU H P, et al. An improved ant colony algorithm for robot path planning [J]. Soft Computing, 2016, 1 (11) : 1-11. DOI: 10.1007/ s00500-016-2161-7.
- [30] XU Y. The effectiveness analysis of multiple-platform cooperative mine searching [J]. Command Control and Simulation, 2013, 35(3): 81-83 (in Chinese).
- [31] FAVARO F, BROLO L, TOSO G, et al. A study on remote data retrieval strategies in underwater acoustic networks [C]//Proceedings of Oceans 2013-San Diego. San Diego, CA: IEEE, 2013: 1-8.
- [32] KARTHIK S. Underwater vehicle for surveillance with navigation and swarm network communication
   [J]. Indian Journal of Science and Technology, 2014, 7(6): 22-31.
- [33] CAO X, ZHU D Q. Multi-AUV underwater cooperative search algorithm based on biological inspired neurodynamics model and velocity synthesis [J]. The Journal of Navigation, 2015, 68(6): 1075-1087.
- [34] YING L L, HE B, ZHANG S J, et al. A modified fast SLAM with simple particle swarm optimization and consistent mapping for AUVs [C]//Proceedings of

Oceans 2014-Taipei. Taipei, China: IEEE, 2014: 1-5.

- [35] LI A G, QIN Z, BAO F M, et al. Particle swarm optimization algorithms [J]. Computer Engineering and Applications, 2002, 38(21): 1–3, 17 (in Chinese).
- [36] ZENG Z, LAMMAS A, SAMMUT K, et al. Path planning for rendezvous of multiple AUVs operating in a variable ocean [C]//Proceedings of the 4th Annual IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CY-BER). Hong Kong, China: IEEE, 2014: 451-456.
- [37] ZHU Y F. Research of intercommunication method of multi-AUV cooperation [D]. Harbin: Harbin Engineering University, 2009 (in Chinese).
- [38] CONSOLINI L, MORBIDI F, PRATTICHIZZO D, et al. Leader-follower formation control of nonholonomic mobile robots with input constraints[J]. Automatica, 2008, 44(5): 1343-1349.
- [39] PENG Z H. Robust adaptive control for formations of marine surface vessels[D]. Dalian: Dalian Maritime University, 2011 (in Chinese).
- [40] CAO Z Q, XIE L J, ZHANG B, et al. Formation constrained multi-robot system in unknown environments [C]//Proceedings of 2003 IEEE International Conference on Robotics and Automation. Taipei, China: IEEE, 2013: 735-740.
- [41] LIANG Y, LEE H H. Decentralized formation control and obstacle avoidance for multiple robots with nonholonomic constraints[C]//Proceedings of 2006 American Control Conference. Minneapolis, USA: IEEE, 2006: 6.
- [42] LEONARD N E, FIORELLI E. Virtual leaders, artificial potentials and coordinated control of groups [C]// Proceedings of the 40th IEEE Conference on Decision and Control. Orlando, USA: IEEE, 2011: 2968–2973.
- [43] ROUT R, SUBUDHI B. A backstepping approach for the formation control of multiple autonomous underwater vehicles using a leader-follower strategy[J]. Journal of Marine Engineering and Technology, 2016, 15 (1): 38-46.
- [44] SHI G F, FANG H J. Fault tolerance of multi-robot formation based on adjacency matrix [J]. Journal of Huazhong University of Science and Technology (Nature Science Edition), 2005, 33(3): 39-42.
- [45] WADA M, SHIMONO T. Formation control of multiple mobile robots based on the modal decomposition by discrete Fourier series expansion [C]//Proceedings of the 7th International Conference on Information and Automation for Sustainability. Colombo, Sri Lanka: IEEE, 2014: 1-6.
- [46] CHEN X P, SERRANI A, OZBAY H. Control of leader-follower formations of terrestrial UAVs [C]// Proceedings of the 42nd IEEE International Conference on Decision and Control. Hawaii, USA: IEEE, 2013: 498-503.
- [47] DESAI J P, OSTROWSKI J P, KUMAR V. Modeling and control of formations of nonholonomic mobile ro-W\_SNIN-research.cor

bots[J]. IEEE Transactions on Robotics and Automation, 2011, 17(6): 905-908.

- [48] ZHANG Y M, MEHRJERDI H. A survey on multiple unmanned vehicles formation control and coordination: normal and fault situations [C]//Proceedings of 2013 International Conference on Unmanned Aircraft Systems. Atlanta, USA: IEEE, 2013: 1087-1096.
- [49] OH K K, PARK M C, AHN H S. A survey of multi-agent formation control [J]. Automatica, 2015, 53: 424-440.
- [50] OU M Y, DU H B, LI S H. Finite-time formation control of multiple nonholonomic mobile robots [J]. International Journal of Robust and Nonlinear Control, 2014, 24(1): 140-165.
- [51] ISMAIL Z H, SARMAN N, DUNNIGAN M W. Dynamic region boundary-based control scheme for multiple autonomous underwater vehicles [C]//Proceedings of Oceans 2012-Yeosu. Yeosu, South Korea: IEEE, 2012: 1-6.
- [52] VASARHELYI G, VIRAGH C, SOMORJAI G, et al. Outdoor flocking and formation flight with autonomous aerial robots [C]//Proceedings of the 2014 IEEE/ RSJ International Conference on Intelligent Robots and Systems. Chicago, USA: IEEE, 2014: 3866-3873.
- [53] PENG X L. Research status and development of underwater robot[J] Robot Technique and Application, 2004, 15(4): 43-47 (in Chinese).
- [54] PETRES C, PAILHAS Y, PATRON P, et al. Path planning for autonomous underwater vehicles [J].
   IEEE Transactions on Robotics, 2007, 23 (2) : 331-341.
- [55] YANG Y. Motion planning and stabilization of multi-vehicle formation[D]. Tianjin: Tianjin University, 2012 (in Chinese).
- [56] ZHAO J B, ZOU Q, LI L, et al. Tool path planning based on conformal parameterization for meshes [J]. Chinese Journal of Aeronautics, 2015, 28 (5) : 1555-1563.
- [57] CHEN S M, HUA Y X, ZHU Z M, et al. Fast flocking algorithm for multi-agent systems by optimizing local interactive topology [J]. Acta Automatica Sini-

ca, 2015, 41(12): 2092-2099 (in Chinese).

- [58] ZHAO D, HU A H, LIU D. Consensus of multiagent networks with intermittent communication via pinning control[J] Information and Control, 2017, 46 (2): 238-242 (in Chinese).
- [59] PENG Z H, WANG D, SHI Y, et al. Containment control of networked autonomous underwater vehicles with model uncertainty and ocean disturbances guided by multiple leaders [J]. Information Sciences, 2015, 316: 163-179.
- [60] PENG Z H, WANG J, WANG D. Distributed containment maneuvering of multiple marine vessels via neurodynamics-based output feedback [J]. IEEE Transactions on Industrial Electronics, 2017, 64 (5) : 3831-3839.
- [61] PENG Z H, WANG J, WANG D. Containment maneuvering of marine surface vehicles with multiple parameterized paths via spatial-temporal decoupling
  [J]. IEEE/ASME Transactions on Mechatronics, 2017, 22(2): 1026-1036.
- [62] CHEN Y Y, TIAN Y P. Directed coordinated control for multi-agent formation motion on a set of given curves[J]. Acta Automatica Sinica, 2009, 35(12): 1541-1549.
- [63] DAI G Z, WANG H L. Rendezvous control for the multi-agent formation with time delay [J] Ship Electronic Engineering, 2017, 37(5): 25-27, 108 (in Chinese).
- [64] BRADY M. Artificial intelligence and robotics [J]. Artificial Intelligence, 1985, 26(1): 79-121.
- [65] FERBER J. Multi-agent systems: an introduction to distributed artificial intelligence[M]. Boston, USA: Addison-Wesley, 1999.
- [66] QARABAQI P, STOJANOVIC M. Statistical characterization and computationally efficient modeling of a class of underwater acoustic communication channels
  [J]. IEEE Journal of Oceanic Engineering, 2013, 38 (4): 701-717.
- [67] LI S H, WANG X Y. Finite-time consensus and collision avoidance control algorithms for multiple AUVs
  [J]. Automatica, 2013, 49(11): 3359-3367.

# 多自主式水下机器人的路径规划和控制技术 研究综述

赵蕊<sup>1</sup>, 许建<sup>1</sup>, 向先波<sup>2</sup>, 徐国华<sup>2</sup> 1 中国舰船研究设计中心, 湖北 武汉 430064 2 华中科技大学 船舶与海洋工程学院, 湖北 武汉 430074

摘 要:自主式水下机器人(AUV)是海洋资源勘探和开发的重要工具,在民用和军用领域都发挥着重要作用。随着 AUV 技术的逐步成熟,通过构建多自主式水下机器人(MAUV)系统,令多个 AUV 协作完成水下作业任务 已成为当前的发展趋势。MAUV系统对提高水下机器人的智能化水平及发展海洋化装备具有重要的理论研究 意义和实用价值。介绍目前 MAUV系统的应用现状和科研进展,并对 MAUV 协同路径规划和集群协同控制技 术等研究热点进行系统化梳理,着重分析人工智能优化和编队协同的关键技术。最后,对 MAUV系统未来的发 展方向进行展望。

关键词:多自主式水下机器人系统;路径规划;集群协同;编队控制 LOWIDADED IFOID WWW.Ship-research.com