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ORIGINAL RESEARCH

Hierarchical formation control technology for multiple autonomous underwater vehicles

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Abstract

The employment of multiple AUVs is to perform missions while maintaining a geometric formation designated. In this paper, communication mechanism based on blackboard is introduced to support cooperation between AUVs, messages are typed according to artificial intelligence. The hierarchical formation control algorithm is proposed, including designing level, generating level, behavioural level, evaluating level. Several formation patterns are designed according to different tasks and requirements. Orderly-Quaternion sets and control matrix are defined for the design of accurate formation geometry. Behaviours of following subgoals and avoiding obstacles enable AUVs team move forward to destination by keeping ideal pattern. Formation length rate and formation maintaining rate are utilised for AUVs team to evaluate the effect of formation. Finally, the presented approach is verified by a simulation of a swarm of AUVs moving through a constrained environment.

KEYWORDS

control nonlinearities, distributed control

1 | INTRODUCTION

The field of underwater robotics has seen significant advancements in recent years, with particular focus on the development and deployment of Autonomous Underwater Vehicles (AUVs). As oceanic exploration and underwater operations become increasingly complex, there is growing interest in leveraging multiple AUVs working in coordinated formations. This approach to underwater missions offers enhanced efficiency, coverage, and robustness compared to single-vehicle operations. The concept of formation control for multiple AUVs draws inspiration from both engineering principles and biological systems, presenting unique challenges and opportunities in the underwater environment.

Cooperative and coordinated multiple autonomous underwater vehicles (AUVs) moving in formation have considerable advantages for many applications including oceanographic measurement, offshore defense, mine sweeping, resource exploitation, pipeline laying. Advantages include the capability to survey large subsea areas more rapidly and economically than could be accomplished with a single vehicle or irregular teams, and increased robustness and efficiency [1–3]. The biologically inspired researches, such as feed-forward networks based on group behaviours in nature like flocking and schooling, shows how animals benefit from moving in the designated formations [4].

A formation of swarms of vehicles is a geometric configuration of the vehicles with specific relative positions and orientation among them. Formation systems consisting of formation generation and formation keeping, deal with the problem of controlling the vehicles in a group in order that the desired formation is obtained and maintained while moving through specific conditions. The advantages and disadvantages of different formation control methods, including virtual structure, artificial potential function, the graph theory, behavioural structure, leader-follower approaches have been presented for AUVs.

The concept of the virtual structure, which was first introduced in Hadi et al. [5], was among the most important formation control approaches. Virtual structure refers to a series of AUV elements that maintain a rigid geometric bond with each other and with a reference coordinate frame. In this approach, the whole group is considered as a single body and utilises the bilateral control architecture. This provides robustness to the structure of formation against internal or external disturbances and lead to better performance. However, it lacks flexibility, cannot be adjusted according to the environment, cannot solve security and obstacle avoidance problems, and has limited applications.

The artificial potential field method was first introduced by Khatib for controlling the mechanical manipulators and mobile robots [6, 7]. In this approach, interaction control forces are used between AUVs in order to generate the desired formation. The attractive and repulsive potential functions are defined. The attractive potential force helps maintain the desired distances between the AUVs and prevent an increase in the distance between the members of the group. The repulsive potential force, however, prevents a decrease in the distance between the vehicles, the probability of collision with each other, and the likelihood of obstacle collision. The method is a simple, intuitive, and computationally efficient obstacle avoidance planning algorithm with certain practical value in specific environments and applications. However, it also has some limitations. For instance, in certain complex environments, robots may get stuck in local optimal solutions preventing them from finding the global optimal path. Furthermore, when multiple obstacles are present in the environment, the superposition of potential fields may lead to potential oscillatory behaviours, affecting the robot's movement efficiency.

Using the graph theory is one of the most common methods in formation control and its stability analysis. In this approach, the vehicles communicate information by means of a predetermined directional communication graph. In this method, the vehicles are defined as ‘nodes’ and the interaction between them is termed as ‘graph edgest’ [8]. The advantage is that it can represent any formation using a graph, but the disadvantage is that it is mainly limited to simulation research and difficult to implement.

Behaviour-based formation control method was first introduced by Balch and Arkin in formation control [9, 10]. This method uses a weighted hybrid of different mission objectives in order to generate vehicle control inputs. Generally, control targets include maintaining desired formation, moving towards the target, avoiding obstacle collisions, and avoiding inter-group collisions. Each of these objectives is prioritised with different gains and the obtained average is given to each vehicle as a control input. Meeting several control objectives simultaneously is one of the benefits of this approach. It is, however, hard to describe the dynamic of the group and guarantee the stability of the whole system, because the kinematic and dynamic features of the vehicle are not taken into consideration. The behavioural structure method is commonly applied in combination with the artificial potential field method.

In the leader-follower approach, one or several AUVs are taken as leaders and the other AUVs are designed as followers. The leaders will follow the trajectory or the designed reference path, but the followers will pursue the leader's status through maintaining the pre-determined desired values of distance and angle in order to generate and retain the shape of the formation [11, 12]. The advantages of this method are its relatively uncomplicated design and implementation, as well as its scalability. Nonetheless, the main weakness of the leader-follower approach lies in its high dependence on the leading vehicle's performance.

This paper focuses on the formation tasks of multiple AUVs in unknown horizontal environments, proposing a communication mechanism based on a blackboard structure and hierarchical formation control technology. Through innovative message-type design, hierarchical control system construction, targeted formation type design, and definition of evaluation indicators for formation effects, efficient, flexible, and evaluable formation control is achieved. These research results not only provide new ideas and methods for the field of AUV formation control but also provide strong support for performance optimisation and effect assessment in practical applications.

Core contributions and innovations of this paper are listed as follows:

1. Design of Message Types Based on Artificial Intelligence Ideas: Differentiated formation message types are designed for the different roles of leader and follower AUVs. This innovation not only improves the pertinence and efficiency of communication but also enhances the system's adaptability to different situations. Through refined message design, each AUV can more accurately understand and respond to information from other AUVs, thereby optimising formation behaviour.
2. Construction of a Hierarchical Formation Control System: A hierarchical architecture (including design layer, generation layer, behaviour layer, and evaluation layer) is introduced, drawing on the advantages of tree structures to achieve clear levels of control and effectively reduce complexity. This structure is not only convenient for management and maintenance but also has good scalability, enabling flexible adaptation to formation tasks of different scales and complexities.
3. Targeted Formation Type Design: Targeted formation types are designed according to different mission objectives and operational requirements. This innovation ensures that the formation strategy closely aligns with actual mission needs, improving the efficiency and success rate of mission execution. Customised formation schemes can better cope with various complex environments and mission challenges.
4. Definition of Evaluation Indicators for Formation Effects: Two evaluation indicators, formation length rate and formation maintenance rate, are defined to quantify and assess formation effects. These indicators not only provide objective standards for measuring formation performance but also provide a basis for subsequent optimisation and improvement. Through precise evaluation and feedback mechanisms, the formation control strategy can be continuously iterated and optimised to enhance overall performance.

2 | COMMUNICATION MECHANISM

In this section, the communication mechanism is introduced for the leader-based hierarchical formation control problem. Only through information sharing and transmitting can the coordination and cooperation between AUVs be fulfilled. So it's critical to establish reasonable communication policy to accomplish formation control. The communication mechanism presented includes two means: (1) AUV detects the ambient environments by various kinds of sensors to obtain the obstacles and boundary constraints information; (2) AUVs exchange information through protocol such as TCP/IP. The two means just like human eyes to obtain formation information for AUVs [13–15].

The AUVs proposed detect surroundings through forward–looking sonar, and the detailed detecting model can be referenced in Das et al. [16]. This paper mainly discusses the communication policy among AUVs by utilising different messages [17, 18]. According to multi-agent theory, the blackboard based communication mechanism is introduced. As shown in Figure 1, each AUV not only can set information on the blackboard info area but can get info from the shared area.

Three types of formation message are defined according to concrete formation commends and artificial intelligence for leader and follower, respectively. As illustrated in Table 1, the messages of leader include inform, order and judge, and the message of follower include inform, request, judge.

We adopt multi-thread program technology to complete interactive communication. Each AUV possesses one thread, and realises synchronisation by using mutex object. In the program, communication is mainly carried out by invoking the global function of CAUVsFormationView.

3 | HIERARCHICAL FORMATION CONTROL

The hierarchical formation control system is designed as illustrated in Figure 2, which includes designing level, generating level, behavioural level, evaluating level. Hierarchical formation has the advantages of tree structure, which allows us to analyse the multi-AUVs team in a systematic way and reduce complexity.

3.1 | Designing level

We set relevant formation parameters in designing level according to missions and requirements, including pattern, size, interval and operating beat-time.

In Table 1, formation missions for multi-AUVs are classified into cruising, surveying, exploring, preying on the invader and transporting. The items to overcome during operating include task complexity, communication, navigation, cooperation and autonomy [19, 20]. Each formation pattern has its own advantage to designated mission, and in this paper we mainly consider five patterns, including V-Shape, Y-Shape, Parallel, Circle and Line (see Table 2).

Formation size is the amount of AUV in the team, which depends on task properties and conditions. The formation size can be set from 3 to 8.

Formation interval is defined as the distance between the front and rear AUV's geometric centre, which rely on AUV's length and sensors equipped. The interval can be set from 20 m to 100 m.

Formation beat-time indicates the planning and coordinating time for leader and follower AUV. And according to operating requirements and environment constrains, the scope of beat-time can be set among 100–500 ms.

3.2 | Generating level

Orderly-Quaternion sets and controlling matrix are utilised to design the accurate formation geometry in generating level. While the orderly-quaternion sets are designed to confirm the adjacent edges between the neighbouring AUV's, the control matrix is derived to ascertain the logic relations between each AUV among formation teams.

There exists one and only one leader in the hierarchical formation system presented. If the team size is N, then N-1

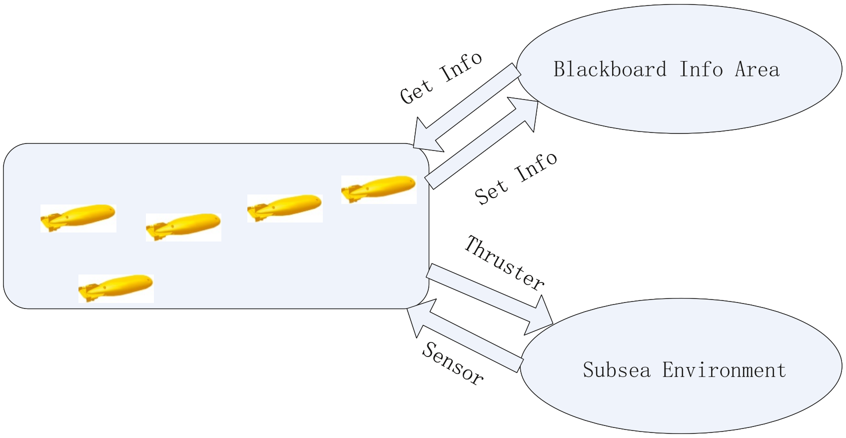

FIGURE 1 Schematic of formation communication architecture.

TABLE 1 Message type of communication for AUV.

Roles	Types	Descriptions
Leader	Inform	Roles: Leader; response: Plan subgoals, add info. to blackboard; ID: followers No.
	Order	Generating: Designed pattern; keeping: Pattern; moving: Forward or stop or swing
	Judge	Judge: bArrived; detect: bThreatened; task: bFinished
Follower	Inform	Roles: Follower; response: Obtain subgoals, get info. from blackboard; ID: followers No.
	Request	Obstacles: Avoiding has high-priority; abandon: Current subgoal; waiting: Next subgoal
	Judge	Judge: bArrived; detect: bThreatened; task: bFinished

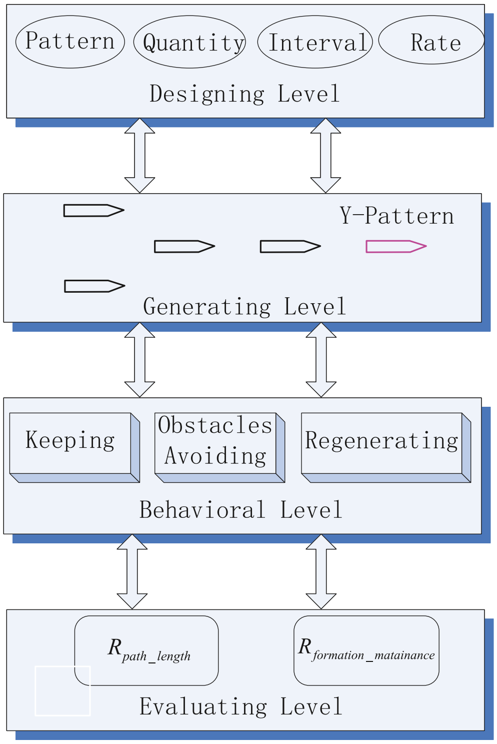

FIGURE 2 Schematic of hierarchical formation systems.

TABLE 2 Multi-AUVs formation scenarios.

Task	Cruise	Survey	Explore	Prey	Transportation
Comp.	L–M	L–M	H	H	L
Comm.	M6	M	H	H	M
Nav.	L	H	H	H	M
Coop.	L	L-M	H	H	H
Auto	L	L	H	H	M
Pattern	V-shape	Y-shape	Parallel	Circle	Line

Note: L-Low, M-Middle, H-High.

adjacent edges will be deduced in the hierarchical system. And the adjacent edge can be expressed as orderly-quaternion sets, which are defined as follows:

$$E_N = \{(V_1, V_2, R_{12}, \sigma_{12}), (V_2, V_3, R_{23}, \sigma_{23}), \ldots, \\ (V_{N-1}, V_N, R_{N-1N}, \sigma_{N-1N})\} \tag{1}$$

where E_N, V_i, R_{ij}, σ_{ij} represent orderly-quaternion sets, nodes, distance and headings between two adjacent nodes, respectively.

According to orderly-quaternion sets designed and the logic relation among nodes, we construct an adjacency matrix. The matrix elements are defined as follows:

$$m_{ij} = \begin{cases} 1, & AUV_i \ is \ the \ follower \ of \ AUV_j \\ 0, & otherwise \end{cases}, i, \ j \\ = 1, 2, \ldots N \ (i \neq j) \tag{2}$$

The features of matrix elements include as follows:

(1) If AUV_i is the leader, then $\sum_j^N \mathrm{m}_{ij} = 0$
(2) If AUV_j is the follower, then $\sum_i^N \mathrm{m}_{ij} \geq 1$
(3) If AUV_j is the tail, then $\sum_j^N \mathrm{m}_{ij} = 0$

In the seven AUVs' team, the orderly-quaternion sets E_7 is given, and through E_7, $M_{7\times 7}$ can be deduced as following:

$$E_7 = \{(1, 2, 50, 5\pi/6), (1, 3, 50, 7\pi/6), (2, 4, 50, 5\pi/6), \\ (3, 5, 50, 7\pi/6), (4, 6, 50, 5\pi/6), (5, 7, 50, 7\pi/6)\} \tag{3}$$

$$M_{7\times 7} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{4}$$

3.3 | Behavioural level

Artificial potential fields developed in behavioural level fall into three sections: the attractive potential field due to the sub goals area, the repulsive potential field due to obstacles region, and the interactive potential field due to adjacent AUVs. The attractive potential is set to drive AUVs to the goal or sub goal point; the repulsive potential field is used to make sure that AUV is repulsed away from the danger, while interactive potential field is defined such that the AUVs keep desired distance from its neighbours. Accordingly, the behaviours proposed in the hierarchical formation control consist of formation maintaining, obstacles avoiding and pattern reconfiguring.

3.3.1 | Formation maintaining

To maintain the designed formation, AUVs need to track the goal or sub goal points to the destination, attractive potential field between AUV and sub goal point is designed to drive AUVs move forward as illustrated in Figure 3.

The attractive potential function is defined in (5), which is related to the distance and headings between AUV and sub goals.

$$F_{PK} = -\sin\delta \cdot \nabla P_{PK}, P_{PK} = \frac{1}{2}\rho_{PK} \cdot \left\| d_{jj'} \right\|^2, \forall j = 1, 2, \ldots, N-1 \tag{5}$$

where ρ_{PK} is the positive gain for the sub goal tracked, $\|d_{jj'}\| = \sqrt{\left(x_j - x_{j'}\right)^2 + \left(y_j - y_{j'}\right)^2}$ is the distance between actual and ideal position of the jth AUV, $\delta = \left|\sigma_{ij'} - \sigma_{ij}\right|$, is the heading error between actual and ideal heading. σ_{ij} and $\sigma_{ij'}$ are the ideal and actual heading between ith AUV and jth AUV (see Figure 3).

We can see from (5), if $\sigma_{ij} = 0$ or $\left\|d_{jj'}\right\| = 0$, then $F_{PK} \equiv 0$. Consequently, when arriving at the sub goal point, AUVs will complete keeping formation designated at the same speed and headings.

3.3.2 | Obstacles avoiding

In this subsection, we consider the collision avoiding problems not only between AUVs and obstacles but among AUVs, as shown in Figure 4. Where Safe area is the critical range when AUV is to be collided by any other objects, Effective area is the formation geometrical field where AUV can keep good shape.

The repulsive force function and potential function are constructed as the following form:

$$F_{CAi} = -\exp(\alpha) \cdot \sin\alpha \cdot \nabla P_{CAi} \tag{6}$$

$$P_{CAi} = \rho_{CA} \cdot \sum_{j=1}^{M} P_{CAi,j}, \forall i = 1, 2, \ldots, N \tag{7}$$

$$P_{CAi,j} = \begin{cases} \frac{1}{2}\left(\frac{1}{d_{ij}} - \frac{1}{d_{safe}}\right)^2, d_{ij} \le d_{safe}, \forall i, j = 1, \ldots, N \\ 0 \qquad d_{ij} > d_{safe} \end{cases} \tag{8}$$

where ρ_{CA} is the positive gain for collision avoiding, d_{ij} is the distance between the ith AUV and jth AUV or jth obstacle, d_{safe} is the minimum safety distance of AUV.

We define the repulsion angle as the angle between the heading of AUV and the tangent on the obstacle plane, which can be expressed as follows:

$$\alpha = \cos^{-1}\frac{V_i \cdot V_j}{\|V_i\|\|V_j\|} \tag{9}$$

$$\sin\alpha = \begin{cases} \sin\alpha & \text{if } \alpha \in \left[0, \frac{\pi}{2}\right] \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

In Equation 10, the AUV will be threatened by obstacles and other AUVs only when $\alpha \in \left[0, \frac{\pi}{2}\right]$. Otherwise, AUV does not need to complete avoiding collisions.

3.4 | Evaluating level

AUVs' team can be interrupted by obstacles ambient and mechanical malfunction when moving underwater. Formation length rate and formation maintaining rate are introduced to assess and analyse the formation effect in the evaluating level.

Definition 1. Formation length rate: Introduce the following expression as the ratio of the average sailing distance of all AUVs with the sailing distance of the leader AUV.

$$R_{fl} = \frac{\frac{1}{n}\sum_{i=1}^{n} d_i}{d_{lead}} \tag{11}$$

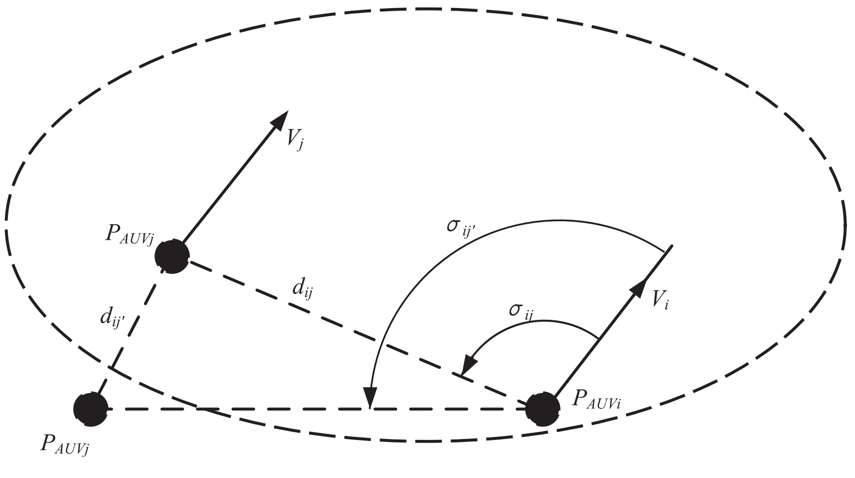

FIGURE 3 Schematic of formation maintaining.

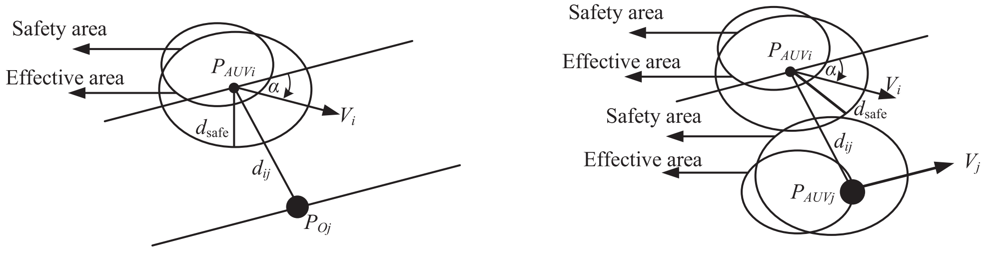

FIGURE 4 Schematic of obstacles avoiding for formation.

C where d_i is the sailing distance of the ith AUV, d_{lead} is the sailing distance of the leader AUV.

Property 1. The ratio has the following property:

$$R_{fl} \ni [1, +\infty) \tag{12}$$

Proof: In the formation system, there exists one fact that $d_i \geq d_{lead}$, due to the disturbance of the obstacles constrained. Accordingly, we have

$$R_{fl} = \frac{1}{n}\sum_{i=1}^{n} d_i/d_{lead} \geq \frac{1}{n} * n * d_{lead}/d_{lead} = 1 \tag{13}$$

This completes the proof. □

One or more AUVs may deviate the trajectory programed owning to the obstacles or boundary restrained when moving to the destination. The less the deviation is, the better the formation could be accomplished. In this paper, we consider as a continuous index to judge the capability of avoiding obstacles.

Definition 2. Formation maintaining rate: Introduce the following expression as the ratio of the average number of sub goals reached by follower AUVs with the number of sub goals planned by the leader AUV.

$$R_{fm} = \frac{\frac{1}{n}\sum_{i=1}^{n} m_i}{m} \tag{14}$$

where m_i is the number of sub goal reached by the ith AUV, m is the number of sub goal planned by leader AUV.

Property 2. The ratio has the following property:

$$R_{fm} \ni [0, 1] \tag{15}$$

Proof: In the formation system, there exists one fact that $m_i \leq m$, due to the threaten of the obstacles constrained. Accordingly, we have

$$R_{fm} = \frac{1}{n}\sum_{i=1}^{n} m_i/m \leq \frac{1}{n} * n * m/m = 1 \tag{16}$$

This completes the proof. □

In this paper, each AUV is driven to follow the sub goal planned in real time. AUVs may abandon some goals for the safety of hardware, which result in the disorganisation of the accurate geometric shape. The more the abundance happened, the worse the formation could be maintained. R_{fm} is deemed as a discrete index to analyse the capability of keeping formation.

4 | SIMULATION RESULTS AND ANALYSIS

In this section, to verify the performance of the above presented algorithm for the hierarchical formation system of multi-AUVs-7, the simulating platforms based Windows are developed by VC++ software. Multi-thread synchronisation technology is adopted to complete formation missions. The entire formation system is designed as a process, in which multiple concurrent threads are set up. And each AUV possesses one thread, meanwhile the process is called as the main thread by the system during formation launching. Each member of the AUVs team can make decisions online and communicate with the blackboard information area.

4.1 | Simulation data

Table 3 depicts the simulating parameters for the three types of formation cases, including formation pattern, size, start and goal position. And also the formation evaluating indexes are showed in the Table 3 for each scenario.

4.2 | Batch scenarios

We now discuss the simulating results obtained from each formation case. Figure 5 illustrates the voyaging course and

TABLE 3 Simulating parameters of formation cases.

Parameter	Size	Start	Goal	R_{fl}	R_{fm}
Y-shape	4	[964, 73]	[84, 601]	1.135	0.883
Parallel	6	[180, 122]	[834, 517]	1.174	0.938
Circle	8	[170, 524]	[879, 103]	1.117	0.943

following sub goals results for the three formation cases, respectively.

Simulation with 4 AUVs: Figure 5 shows the final maps obtained for Y-Shape formation moving through complex space. AUV3 abandons some sub goals to prevent from colliding with obstacle 2 when the team arriving at obstacle 2 ambient. When reaching the vicinity of obstacle 4, the leader AUV0 alters the original course, and accordingly the followers make the same decision to trace the new trajectory.

Simulation with 6 AUVs: Figure 6 shows the final maps obtained for Parallel-Shape formation moving through complex space. The team can maintain a good shape when moving from start point to destination except threatened by obstacle 2 and obstacle 3. As illustrated in Figure 6, when escaping from the danger of the obstacle 3, AUV3 resets to the position desired.

Simulation with 8 AUVs: Figure 7 shows the final maps obtained for Circle-Shape formation moving through complex space. When getting to the ambient of the obstacle 1, AUV4 takes priority to avoiding obstacle, and its trajectory is heavily influenced. Meanwhile, other AUVs are not interfered and keep the designed formation.

Compared with the above simulating scenarios, the formation effectiveness is not only related with underwater environments, but has relationship with the formation parameters. Consequently, multi-factors should be considered to carry out formation tasks. Having analysed and discussed the results, we proceed to draw concluding marks.

4.3 | Discussions

The simulation design for the formation task of multiple Autonomous Underwater Vehicles (AUVs) is primarily based on a constrained horizontal environment with obstacles, aiming to emulate the real-world ocean's unknown, uncertain, and complex environment. This design carries significant practical application value. In the face of such unknown and complex environments, effective communication mechanisms and intelligent control strategies become crucial for the successful completion of formation tasks. The main strengthens are as the followings:

(1) Message Type Design Based on AI Principles: Differentiated formation message types have been designed for the distinct roles of leader and follower AUVs. This innovation not only enhances the pertinence and efficiency of

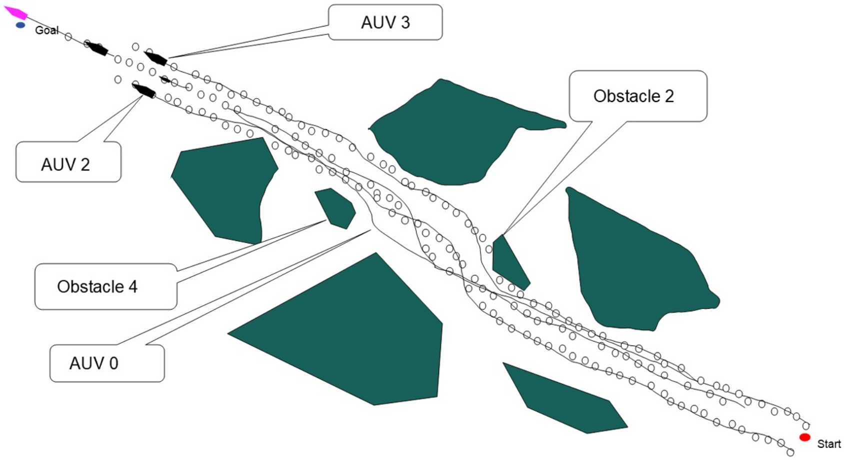

FIGURE 5 AUVs moving through obstacles space by Y-shape.

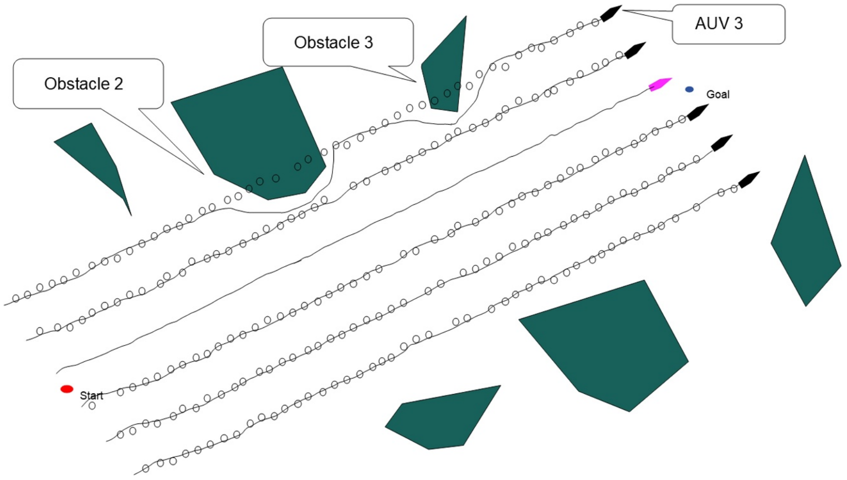

FIGURE 6 AUVs moving through obstacles space by Parallel-shape.

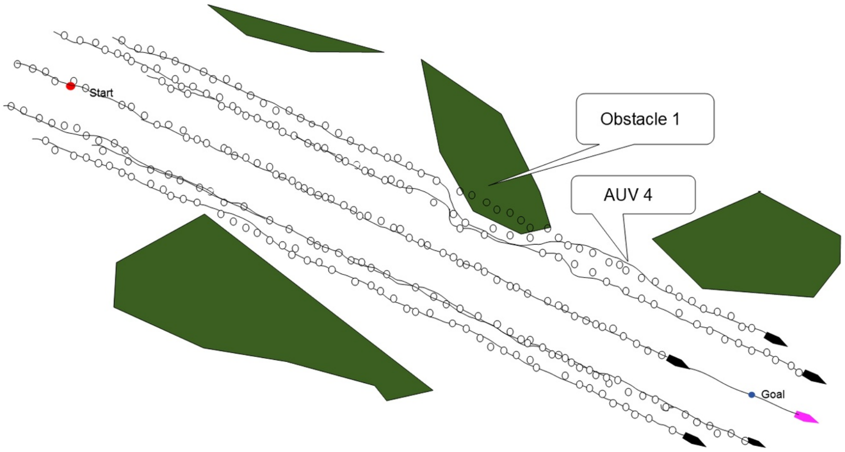

FIGURE 7 AUVs moving through obstacles space by Circle-shape.

communication but also strengthens the system's adaptability to different scenarios. Through refined message design, each AUV can more accurately understand and respond to information from other AUVs, thereby optimising formation behaviour.

(2) Construction of a Hierarchal Formation Control System: A layered architecture (including design, generation, behaviour, and evaluation layers) has been introduced, drawing on the advantages of tree structures to achieve clear control hierarchy and effective complexity reduction. This structure is not only convenient for management and maintenance but also exhibits good scalability, enabling flexible adaptation to formation tasks of different scales and complexities.
(3) Tailored Formation Type Design: Targeted formation types have been designed according to different mission objectives and operational requirements. This innovation ensures that formation strategies closely align with actual task needs, improving the efficiency and success rate of task execution. Customised formation plans allow for better responses to various complex environments and task challenges.
(4) Definition of Formation Effect Evaluation Indicators: Two evaluation indicators, formation length rate and formation maintenance rate, have been defined to quantify and assess formation effectiveness. These indicators not only provide objective standards for measuring formation performance but also serve as a basis for subsequent optimisation and improvement. Through precise evaluation and feedback mechanisms, formation control strategies can be continuously iterated and optimised, enhancing overall performance.

Through innovative message type design, layered control system construction, tailored formation type design, and the definition of formation effect evaluation indicators, efficient, flexible, and evaluable formation control has been achieved. These research findings not only offer new ideas and methods for the field of AUV formation control but also provide robust support for performance optimisation and effect evaluation in practical applications.

5 | CONCLUSION

In this paper, we have discussed hierarchical formation control strategy according to the issues and tasks in the formation systems. The communication mechanism based blackboard information area is developed for the cooperation between AUVs, messages for leader and follower AUV are typed according to artificial intelligence. The leader-based hierarchical formation control system proposed includes designing level, generating level, behavioural level, evaluating level. Several formation patterns are devised according to different tasks and requirements. Formation length rate and formation maintaining rate are novelly defined to evaluate the formation results.

And for the future works, there are still some problems to be tackled with. All these remarks should be considered carefully before the implementation on real hardware and corresponding experiments are operated.

(1) In the real underwater environments, there could be existed not only static obstacles but more dynamic objects, such as fish schooling and moving invaders. Hence, the dynamic obstacles should be taken into account in the formation system.
(2) The leader AUV maybe in deadlock status and occur mechanical malfunction, and so that can't lead the other AUVs to the target. Consequently, we should construct the transforming policy to select a new leader to complete formation.
(3) We should further discuss the formation control in 3D space for the real applications.

Researches and applications of these items are expected to enable AUVs formation to challenge more complex and practical missions, overcoming more adverse underwater conditions.

AUTHOR CONTRIBUTIONS

Shibo Fan and Pengfeng Lin prepared the manuscript of this paper. Jie Jiao and Qingzuo Meng helped to perform necessary data analyses and numerical computations.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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