COMPLEX SYSTEM MODELING AND SIMULATION
ISSN 2096-9929 01/06 pp 1–14
Volume 1, Number 1, March 2021
DOI: 10.23919/CSMS.2021.0003

Overview of Research on Transformation of Multi-AUV Formations

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Abstract: Because of their wide detection range and rich functions, autonomous underwater vehicles (AUVs) are widely used for observing the marine environment, for exploring natural resources, for security and defense purposes, and in many other fields of interest. Compared with a single AUV, a multi-AUV formation can better perform various tasks and adapt to complex underwater environments. With changes in the mission or environment, a change in the UAV formation may also be required. In the last decade, much progress has been made in the transformation of multi-AUV formations. In this paper, we aim to analyze the core concepts of multi-AUV formation transformation; summarize the effects of the AUV model, underwater environment, and communication between AUVs within formations on formation transformation; and elaborate on basic theories and implementation approaches for multi-AUV formation transformation. Moreover, this overview includes a bibliometric analysis of the related literature from multiple perspectives. Finally, some challenging issues and future research directions for multi-AUV formation transformation are highlighted.

Key words: autonomous underwater vehicle; multi-AUV formation; formation transformation; formation control

1 Introduction

An autonomous underwater vehicle (AUV) is a complex system that integrates sensor detection, information fusion, vehicle control, and other technologies and is widely used in marine exploration, underwater pipeline detection, hunting, and other scientific and military tasks. To date, various AUVs have been developed and practically applied[1]. Recent breakthroughs in technical specifications such as submergence depth and endurance have provided strong support to AUVs in performing complex underwater tasks[2].

Because of the complexity of the underwater environment and the increasing difficulty of tasks, a single AUV can have difficulty performing complex tasks, whereas multi-AUVs can cooperatively execute tasks and achieve greater efficiency, which is also suitable for a complex underwater environment. Therefore, multi-AUV cooperative control has important research value. Formation control, an important aspect of cooperative control, refers to the formation of multiple agents to meet task requirements and environmental constraints. Research on formation control originated from observations of the behavior of some biological flocks such as birds, fish, and bees. Formation is a special organization form of flock, and formation control is closely related to flocking control. The main difference between the two is that the distance between and relative orientations of agents in formation control are fixed, whereas there is no such constraint among agents in flocking control[3]. In formation control, a dynamic model of the agents needs to be developed, and information links should be established among agents in the formation. In this case, to adjust its position, speed, and other factors, each agent can obtain state information and task instructions from its neighbors via the established links.

According to the different behaviors of a formation, the formation control process can be divided into the tasks of generation, maintenance, and transformation

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Manuscript received: 2021-02-16; revised: 2021-02-18; accepted: 2021-02-22

of the formation. Formation generation refers to the organization of randomly distributed agents into a desired formation. Formation maintenance means that each agent maintains fixed relative positions with respect to the others in the process of advancing. In formation transformation, a formation changes from its current shape to a new shape. Formation generation and transformation share similar implementation methods, because their ultimate goal is to make the formation achieve a specific shape; however, their application scenarios and initial state of formation are different, which can lead to different processes of forming a new shape. In this paper, the main factors influencing formation transformation and some specific implementation methods are investigated in detail.

The formations of various agents (such as unmanned aerial vehicles, unmanned ground vehicles, unmanned surface vessels, or satellites) need to change shape under certain circumstances, and transformation has been the focus of many studies. On the one hand, the formation transformation methods of different agents share some similarities in terms of controller design and path planning methods. On the other hand, there are also many differences, including different agent models, working environments, and tasks. Compared with other multiagent formations, a unique characteristic of the multi-AUV formation is the poor communication conditions. Environmental factors such as water depth, water quality, and light field can have a negative impact on communication devices, thus reducing the stability of the communication and information quality. This problem presents great challenges for realizing effective multi-AUV formation transformation.

This paper presents an overview of the literature on formation transformation published in the last decade (2010–2020), as most studies were conducted during this period. The searched databases include CNKI, Web of Science, and EI. Figure 1 shows the number of papers published in the past ten years, from which it is evident that a significant increase occurred between 2017 and 2020.

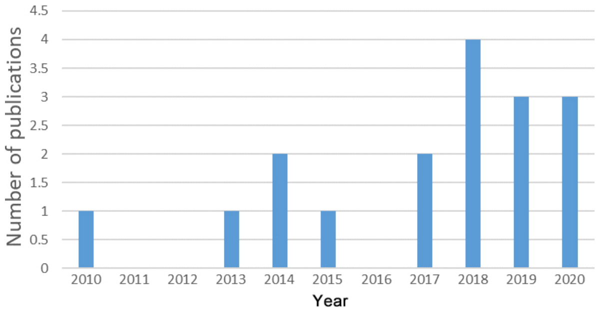


Fig. 1 Number of publications (2010–2020). Index terms: (AUV or Unnamed Underwater Vehicle (UUV) and formation transformation or dynamic formation).

In recent years, some scholars have summarized the research on AUV formation control. Reference [2] presented the research status of AUV systems and analyzed the trend in the development of intelligent AUVs with respect to sensing, control method, and fault diagnosis technology. In Ref. [4], the formation control problem was divided into two parts, i.e., the internal adjustment and the tracking of expected trajectories, and discussed the challenges presented by AUV damage, communication, collision avoidance, and obstacle avoidance. In Ref. [5], various formation control strategies were introduced in detail. In Ref. [6], the formation control problem was divided into formation generation and formation tracking. However, none of these reports considered formation transformation in detail. As such, in this paper, we present an overview of works related to the main influencing factors (including internal and external environmental factors) and basic theories of multi-AUV formation transformation. We classify the specific implementation approaches according to different control methods and implementation layers and discuss future research directions.

The rest of this paper is organized as follows. In Section 2, we introduce several key problems and the main factors influencing multi-AUV formation transformation and analyze some core concepts of formation transformation. In Section 3, we classify the implementation approaches used in multi-AUV formation transformation with respect to formation control methods and implementation layers. In Section 4, we present a statistical analysis of related studies in the last ten years from multiple perspectives. In Section 5, we consider future research directions, and we conclude the paper in Section 6.

2 Key Problems and Main Factors Influencing Multi-AUV Formation Transformation

In this section, we present some key problems associated with multi-AUV formation transformation and describe related research with respect to these problems. In addition, we introduce the main factors influencing multi-AUV formation transformation, including the AUV model, formation structure, underwater environment, and some constraints. These factors provide a foundation for understanding the difficulties associated with multi-AUV formation transformation, classifying transformation methods, and future research directions.

2.1 Key problems of multi-AUV formation transformation

In this subsection, we consider several key problems facing multi-AUV formation transformation. The details are as follows:

Q1 How to define a formation?

Remark 1 A clear definition of formation provides a basis for studying formation transformation, which facilitates a more accurate description of the formation before and after transformation.

Q2 Under what circumstances does multi-AUV formation need to change?

Remark 2 The following are circumstances that require a change in the shape of the multi-AUV formation:

(1) Obstacle avoidance[7],

(2) Hunting[8],

(3) Damage to some AUVs[9],

(4) Target search and tracking[10], and

(5) Environmental sampling at different water depths[11].

Q3 Into which shapes does a multi-AUV formation need to change?

Remark 3 Proper shapes depend on both environment and task. For example, when a multi-AUV formation is required to get through a narrowed region to search for a target, it may change into a queue from a row though the latter is beneficial for scanning the environment to detect a target.

Q4 How to evaluate the quality of the target formation?

Remark 4 This problem is related to Q3. Furthermore, it quantifies formation performance and helps to determine the shape into which a multi-AUV formation must transform. The effectiveness of different formations often varies with the task and environment, with the expected performance of the target formation obtained using an optimization method.

Q5 How does a multi-AUV formation change from its current formation to the desired target formation?

Remark 5 This problem involves the determination of the specific implementation method of formation transformation.

Q6 For multi-AUV formations of a certain scale, what is the size limit for those formations?

Remark 6 This question can be stated another way: "*How many different shapes can a formation of a certain scale transform into*?" Because of the limitations associated with the AUV model, environment, and communication and sensing conditions, the types of shapes into which a multi-AUV formation can transform are limited. If a given formation is abstracted as a state in state space, the range of changeable AUV formations is a finite set of states in this space.

Q7 How to evaluate the implementation method of formation transformation?

Remark 7 This problem can be extended to the problem of optimal formation transformation. Unlike Q4, which focuses on the result of the formation transformation, this problem focuses on the transformation process from the current to the target formation.

2.2 Main factors influencing multi-AUV formation transformation

In this subsection, we introduce the main factors that influence multi-AUV formation transformation, including the AUV hydrodynamic model, formation structure, and underwater environment and communication conditions. We also consider the constraints on formation transformation with respect to these factors.

2.2.1 AUV motion model

An AUV is characterized by an underactuated dynamic structure. Its propulsion system includes a rudder and the main propeller, which enable the AUV to have independent control inputs with respect to the surge, yaw, and pitch[12]. A three-degrees-of-freedom (3-DOF) AUV motion model can be expressed as Eq. (1), in which $\boldsymbol{\mu} = (y_g, x_g, \alpha)^{\mathrm{T}}$ denotes the coordinates and orientation of the AUV in the Cartesian coordinate system and $\boldsymbol{v} = (u, v, r)^{\mathrm{T}}$ denotes the surge, sway, and angular velocities of the AUV in the body coordinate system[13]:

$$\begin{aligned} \dot{\mu} &= R\boldsymbol{v}, \\ M\dot{\boldsymbol{v}} &= \boldsymbol{\tau} - C(\boldsymbol{v})\boldsymbol{v} - D(\boldsymbol{v})\boldsymbol{v} \end{aligned} \tag{1}$$

R is the transformation matrix used to achieve transformation between the Cartesian and body coordinate systems. It can be represented by Eq. (2).

$$R = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ \sin\alpha & -\cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

For all α, $R^{\mathrm{T}}R = I$, $\|R\|_2 = 1$.

M is the inertia matrix of the system, with $M = M^{\mathrm{T}} > 0$. $C(\boldsymbol{v})$ is a skew-symmetric matrix with Coriolis and centripetal terms, $C(\boldsymbol{v}) = -C(\boldsymbol{v})^{\mathrm{T}}$. $D(\boldsymbol{v})$ is a nonlinear damping matrix. The methods used to calculate $M, C(\boldsymbol{v})$, and $D(\boldsymbol{v})$ can be found in Ref. [13]. $\boldsymbol{\tau} = (\tau_u, \tau_v, \tau_r)^{\mathrm{T}}$ is the control input set, which is related to propeller speed and rudder angle, among other factors. Because of the limitations inherent in the AUV structure, the control inputs have upper limit values[13].

2.2.2 Multi-AUV formation structure

The structure of a formation includes its geometric configuration and communication topology, which are presented in detail below.

(1) Geometric configuration

The geometric configuration of a formation, i.e., its shape, represents the positional relationships of the agents in the formation. Reference [14] defines the geometric configuration of a formation as the geometric information retained after the removal of the formation's rotation and translation information. According to Ref. [15], formation control is the maintenance of an ideal spatial pattern by multiple agents. There are several ways to describe a formation. References [15, 16] introduced three descriptions: (1) absolute coordinates of the agents; (2) relative position vectors between agents, including the Euclidean distances and relative angles of sight; and (3) Euclidean distances between several pairs of agents (distance-based approach). Currently, most researchers use the second or third method to describe a formation and set its parameters as fixed values. However, in more general application scenarios, the parameters of a formation can be changed within a bounded interval. In this paper, we define a formation, precise formation, and an imprecise formation as follows:

Definition 1 A formation $\mathfrak{B}$ is defined as a parameter set $\{q_1, q_2, \ldots, q_k\}$, where K is the total number of parameters in the set and $q_k (k \leqslant K)$ is the Euclidean distance or the relative angle of sight between agents.

Definition 2 Given a formation $\mathfrak{B} = \{q_1, q_2, \ldots, q_K\}$, if q_k is a constant for $\forall k \leqslant K$, $\mathfrak{B}$ is said to be a precise formation and is denoted by $\mathfrak{B}^*$.

Definition 3 Given a formation $\mathfrak{B} = \{q_1, q_2, \ldots, q_K\}$, if $\exists k \leqslant K$ and q_k is a variable in an interval $\left[q^-, q^+\right]$, $\mathfrak{B}$ is said to be an imprecise formation and is denoted as $\mathcal{F}^*$, where q^- and q^+ are determined by the working environment of the agents, the safe distance between them, and their communication and sensing ranges. From Definition 2, we can see that an imprecise formation is a set of multiple precise formations, $\mathcal{F}^* = \left\{\mathfrak{B}_1^*, \mathfrak{B}_2^*, \ldots\right\}$.

The scale of the multi-AUV formations in most studies has been relatively small (ranging from 2 to 10), and the precise formation definition has been applied. However, when a large number of agents exist in a formation, a precise formation must manage a massive amount of parameter data, which increases the computational burden. Therefore, some studies have used the imprecise formation definition. For example, Refs. [8, 11] used a boundary to represent the formation, with the AUVs evenly distributed on and inside the boundary. The distance between AUVs is variable within a certain interval. Some of the formations studied have contained hundreds of AUVs. In Ref. [8], the radial basis implicit function (RBIF) was used to represent the formation boundary. RBIF can also be used to judge whether an agent is on/outside/inside the boundary. A formation with 30 AUVs was considered in this simulation experiment. An imprecise formation has fewer constraints on the positional relationships of the AUVs and is more suitable for a large-scale formation compared with a precise formation (Q1).

The geometric configuration of a formation may be different for different tasks. For example, the goal of a target-search formation is to maximize the coverage rate and minimize the overlapping rate as much as possible. Therefore, agents in the formation are expected to be dispersed. When the formation is tracking a moving target, the goal is to minimize the target loss rate and obtain as much target information as possible, so it is desirable that agents in the formation can be aggregated[17]. Figure 2 shows examples of the formations used for target search and tracking. In addition, collisions need to be avoided when encountering different underwater terrains or obstacles and different formations (Q3). The desired formation can be obtained by optimization. Formation optimization is an NP-hard problem. References [18–20] provided evaluation indexes for formation structures, e.g., their invulnerability. In Ref. [21], a method for optimizing the parameters of a triangular formation of three missiles is investigated, with the relative position vectors between missiles taken as decision variables, the triangular structure taken as a constraint, and the vertical search range, search width, and combat range taken as evaluation indexes (Q4).

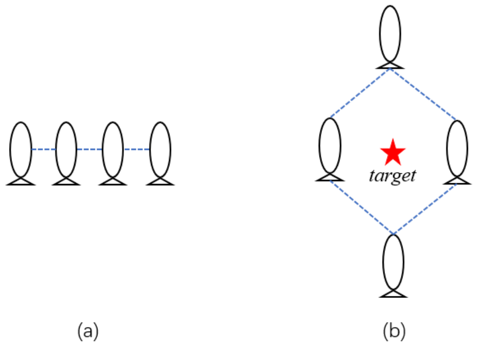


Fig. 2 Formations used for (a) target search and (b) target tracking.

(2) Communication topology

The term communication topology refers to the information transmission paths among agents in a formation. The successful implementation of tasks requires effective communication among agents. Through information transmissions, each agent can adjust its current working state to complete tasks efficiently. The communication modes of a formation include explicit and implicit communication. Explicit communication relies on communication media and devices to transmit specific information, including broadcast and point-to-point communication. Broadcast communication may cause information to be ignored, and channel conflict problems may exist in point-to-point communication[22]. Explicit communication technologies for use underwater commonly include optical, acoustic, and magnetic field communication technologies, among which underwater acoustic communication is the most mature and the most commonly used. Table 1 summarizes the advantages and disadvantages of these three communication technologies[23].

Implicit communication means that each agent obtains information through its own detection devices and then uses algorithms to process the information. Underwater detection devices can be broadly divided into acoustic and optical devices[24]. Sonar is the most mature underwater acoustic device, including multibeam, side-scan, and synthetic aperture sonar. The most commonly used underwater optical device is the underwater camera[2]. The information obtained by AUVs includes position, velocity, and behavior.

In Ref. [25], a conditional random field was applied to capture the behavior sequences of neighboring AUVs. AUVs perform certain actions in specific locations to express their role or state. In Ref. [26], the hidden Markov model was used to identify the behaviors of AUVs. In Ref. [27], a vector-light device was installed on an AUV to transmit information. By adjusting the power of lamps, different modes of vector-light beams can be emitted to represent different information.

Graph theory can be employed to model a communication topology. Based on the one-way/two-way communication between agents, the communication topology can be modeled as a directed/undirected graph. As an example, the mathematical expression for a directed graph is as follows: $D = (V, E, A)$ is used to represent the communication topology of a formation, in which $V = \{1, 2, \dots, N\}$ denotes the set of all agents in the formation, and E is the set of all edges. If AUV i can receive information from AUV $j (i, j \leqslant N)$, there is a directed edge from AUV j to i with the edge $\langle j, i\rangle \in E$. $A = (a_{ij})_{N\times N}$ is the adjacency matrix of D. If there is a directed edge $\langle j, i\rangle \in E$, $a_{ji} = 1$. Otherwise, $a_{ji} = 0$[28]. One precondition for executing tasks in a coordinated manner is that the communication topology of the formation is connected.

The relationship between the communication topology and formation geometry can be mapped. Generally, a given communication topology can support many formation geometries. A rigid graph[29,30] can be used to determine the formation structure through the joint description of the topological and geometric spaces. Let g_i be the position of AUV i. If $\|g_i - g_j\|$ is a constant for $\langle i, j\rangle \in E$, the formation can be modeled as a rigid graph. A formation with a rigid graph must be a precise formation, and a topological graph that corresponds to an imprecise formation must not be a rigid graph.

Table 1 Some advantages and disadvantages of different underwater communication technologies.

Communication technology	Advantage	Disadvantage
Optical communication	Low cost, low power consumption, large bandwidth, and high transmission rate	Serious disturbance caused by underwater environment
Acoustic communication	Long transmission distance	Low transmission rate, limited bandwidth, long communication delay, and disturbance caused by water quality, water pressure, and underwater noise
Magnetic field communication	Stable channel	Short transmission distance

2.2.3 Underwater environment

(1) Spatial dimension

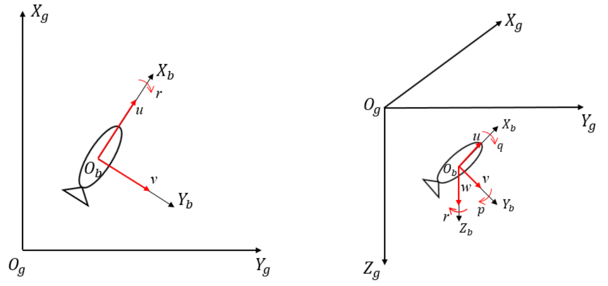
The motion of an AUV is different in two-dimensional (2D) and three-dimensional (3D) space. In 2D space, the 3-DOF motions of an AUV include surge, sway, and yaw. In 3D space, the six-degrees-of-freedom motions include surge, sway, heave, yaw, pitch, and roll. The coordinate systems in 2D and 3D space also differ: a north–east coordinate system is usually applied in 2D space, and a north–east–down coordinate system is generally applied in 3D space. The motion of an AUV and the relative positional relationships among AUVs also differ in 2D and 3D space. Table 2 explains some symbols used.

In 3D space, owing to the coupling of motions with several degrees of freedom, the rolling motion can be ignored, and a five-degrees-of-freedom motion model of the AUV can be obtained. In Eq. (1), let $\boldsymbol{\mu} = \left(y_g, x_g, z_g, \alpha, \theta\right)^{\mathrm{T}}$ and $\boldsymbol{v} = (u, v, w, r, p)^{\mathrm{T}}$. Equation (3) shows the transformation matrix between the Cartesian and body coordinate systems in 3D space. Figure 3 shows the motion of an AUV in 2D and 3D space.

$$R = \begin{pmatrix} \cos\theta\cos\alpha & -\sin\theta & \cos\theta\sin\alpha & 0 & 0 \\ \sin\theta\cos\alpha & \cos\theta & \sin\theta\sin\alpha & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \dfrac{1}{\cos\alpha} \end{pmatrix} \tag{3}$$

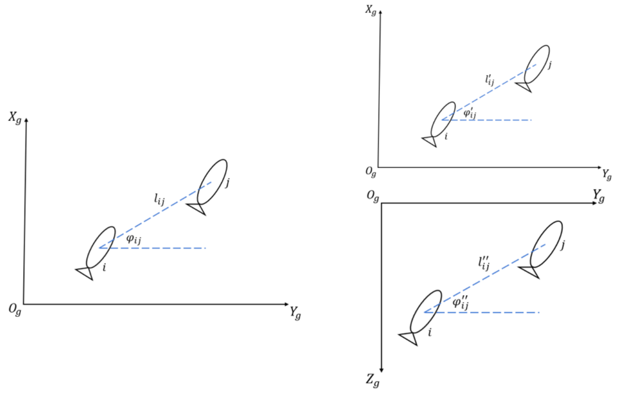
Table 2 Explanations of symbols in Figs. 3 and 4.

Symbol	Explanations
α, θ	Yaw angle and pitch angle
u, v, w	Surge velocity, sway velocity, and heave velocity
r, p, q	Yaw angle velocity, pitch angle velocity, and roll angle velocity
l_{ij}, φ_{ij}	Euclidean distance and relative angle of sight between AUVs in 2D space
l'_{ij}, l''_{ij}	Projection of Euclidean distance between AUVs on $Y_g O_g X_g$ and $Y_g O_g Z_g$ planes in 3D space
$\varphi'_{ij}, \varphi''_{ij}$	Projection of relative angle of sight between AUVs on $Y_g O_g X_g$ and $Y_g O_g Z_g$ planes in 3D space



(a) (b)

Fig. 3 Motion of an AUV in (a) 2D and (b) 3D space.



(a) (b)

Fig. 4 Relative positional relationships among AUVs in (a) 2D and (b) 3D space.

Figure 4 shows the different relative positional relationships among AUVs in 2D and 3D space. Generally, the horizontal motion of the AUV is decomposed to reduce the computational cost. In the vertical direction, an AUV can change its submergence depth through buoyancy adjustment and other methods to adapt to different mission requirements and underwater terrains[12].

(2) Environmental complexity

Underwater environments are unpredictable and time varying; many factors can affect the motion of an AUV in such environments, including the light field, complexity of the underwater terrain, water salinity, water pressure, water depth, underwater obstacles, and currents[24]. Many researchers have studied the influence of underwater obstacles and currents on AUVs. The types of underwater obstacles are complex. According to the different maneuvering actions required, obstacles can be categorized as either static (reef, sunken ship, coastal baseline, etc.) or dynamic (underwater organisms). Based on their different volumes and shapes, obstacles can be abstracted into points, circles, boundary lines, columns, and spheres[12]. When sailing, AUVs are inevitably disturbed by currents. Although current velocity sensors can be installed, their measurement accuracy is considerably affected by temperature. Some studies have treated currents as a kinematic disturbance, assuming that a current has an unknown steady velocity, which is denoted by v_c and is estimated by an observer. In Eq. (1), $\boldsymbol{v} = \left(u - v'_c, v - v''_c, r\right)^{\mathrm{T}}$, where v'_c and v''_c represent the projections of v_c onto the two axes[31]. In Ref. [32], the current disturbance acting on an AUV is considered an unknown bounded time-varying signal with a finite rate of change, which is estimated online by an observer designed for that purpose.

2.2.4 Main constraints in multi-AUV formation transformation

Given the characteristics of the AUV dynamics and working environment, in this subsection, we summarize the main constraints on multi-AUV formation transformation, including the AUV autocorrelation, environmental, and AUV cooperation constraints. Table 3 provides brief descriptions of these constraints.

3 Classification and Analysis of Multi-AUV Formation Transformation Methods

Based on the content in Section 2 above, here we analyze existing formation transformation methods with respect to different formation control methods and layers. Common formation control strategies used for multi-AUV formations include the leader–follower, virtual structure, artificial potential field, and behavior-based methods. In Ref. [4], formation transformation is divided into three layers: path planning layer (plans an ideal path that meets the given constraints), collaborative management layer (determines the path and speed of each agent), and path control layer (smooths paths to enable the required agent mobility). Herein, we divide the formation transformation into two layers: the planning and bottom control layers. Most of the formations reported in the literature are small in scale, and the formations before and after transformation are precise (Definition 2).

3.1 Formation control methods used for multi-AUV formation

AUV formation control methods comprise the formation model and the design of the formation controller, which serve as the basis for multi-AUV formation transformation. To transform a multi-AUV formation in a complex mission scenario or underwater environment, different methods can be combined to produce a new one. The following is a detailed analysis of the four control methods used in some studies.

3.1.1 Leader-follower method

In the leader–follower method, first proposed by Cruz[33], agents in a formation are divided into two groups: leaders and followers. Leaders control the movement of the entire formation, while followers adjust their movements according to their relative positional relationship with their leaders and the instructions conveyed by the leaders. In Ref. [34], a leader–follower method was used to design a formation error model. In Ref. [35], a virtual leader was introduced into a formation of underwater gliders, with the position of each agent confirmed by the observation of a virtual leader and the use of an artificial potential field method to transform the shape of the formation from circular to rectangular. In Ref. [36], each follower AUV determines its desired position in the formation according to the position of its leader. When the formation enters a narrow area, it changes from a herringbone to a straight line. In Ref. [37], each follower AUV obtains its own waypoint at the next moment based on the historical and current positions of its leader, with the formation transforming from a line to a pentagon.

Although frequently applied, the leader–follower method has the obvious shortcoming of relying excessively on the leaders. If one leader is damaged, the communication topology may become disconnected, resulting in the destruction of the formation

Table 3 Main constraints in multi-AUV formation transformation process.

Constraint		Description
AUV autocorrelation constraints	Energy consumption	The energy of an AUV is limited.
	Velocity	Because of the dynamic constraints of AUVs, there is an upper limit of velocity.
	Curvature	AUVs have an underactuated structure, so their curvature is limited.
	Submergence depth	Because of the limitations in the AUV's structure, there is an upper limit to the AUV's submergence depth.
	Load	The type and quantity of devices carried on an AUV are limited.
Environmental constraints	Obstacle avoidance	AUVs cannot collide with underwater obstacles.
Cooperation constraints	Topological connectivity	The connectivity of a formation communication topology is a sufficient condition for multiple AUVs to reach a consistent state when they advance or cooperatively complete missions.
	Geometric structure	The formation maintains a specific geometry that maintains the connectivity of the communication topology and improves operational efficiency.
	Distance between AUVs	It is desired that no collision occurs between AUVs. Too close a distance between AUVs will severely impact their motion, so the distance between AUVs must be specified as not less than a certain value.

configuration and the potential failure to execute the task.

3.1.2 Virtual structure method

The virtual structure method, first proposed by Tan and Lewis[38], sets the desired formation as a virtual structure and determines the kinematic and dynamic characteristics and position of each point in this structure. Each agent determines and tracks its own desired position according to the virtual structure. References [9, 10, 39, 40] designed virtual structures for multi-AUV formations and assigned the desired position to each AUV. Reference [7] first determined the center point of the formation and then formed a virtual structure around the center. Each AUV also tracked its desired position in the virtual structure.

3.1.3 Artificial potential field method

In the artificial potential field method, first proposed by Khatib[41], an artificial potential field is set for each agent, desired position, and obstacle. The potential field interactions among them generate a potential field force that can drive each agent toward its desired position and away from obstacles. The artificial potential field method is frequently applied to obstacle avoidance and was applied in Refs [8, 9, 39, 42] to enable a multi-AUV formation to pass through narrow obstacle-ridden areas. In Refs. [9,39,42], after determining the desired position, each AUV uses the artificial potential field method to approach its desired position and avoid obstacles. In Ref. [8], the virtual structure method was combined with the artificial potential field method to enable the formation to pass through obstacle-ridden areas by contraction and expansion.

3.1.4 Behavior-based method

The behavior-based method, first proposed by Brooks[43], was first applied to the multi-AUV field by Pan[12] and Kumar and Stover[44]. This method decomposes a task into a series of subtasks in which basic behaviors such as moving straight ahead, turning left, and turning right are combined as multiple behaviors to accomplish the desired tasks. Few studies have applied this method of formation transformation. In Ref. [45], a fuzzy rule set was designed based on the driving behavior of vehicles in various situations. With each AUV performing a series of basic behaviors, the formation can contract and expand to avoid obstacles.

3.2 Formation transformation in different layers

In this subsection, we divide multi-AUV formation transformation into planning and bottom control layers. The methods used in the planning layer focus on assigning each point in the target formation to each AUV and planning a path for each AUV from its current to the desired position. The methods used in the bottom control layer focus on the design of an AUV formation controller that adjusts the kinematic and dynamic states of each AUV, such as the position and velocity, to enable the multi-AUV formation to transform into the desired shape and continue to move forward.

3.2.1 Planning layer

In Ref. [46], the implementation of the planning layer was further divided into the desired position assignment and path planning. First, each agent is assigned a position in the target formation, and then a path is planned from the current to the desired position. Finally, the formation is transformed from a quadrangle to a line. Reference [47] improved the particle swarm optimization (PSO) algorithm and applied it to multi-AUV formation transformation. First, each AUV is assigned to the nearest desired position. Then, each AUV is regarded as a particle in the PSO algorithm, and its desired position replaces the global optimal solution in the PSO speed update rule. Through iterative optimization, the AUV gradually moves toward its desired position. When the distance between the AUV and its desired position is less than a preset value, the optimization process is terminated. However, the speed update rule does not meet the curvature constraint of AUVs, and collision avoidance between AUVs is not considered when planning the paths. In Refs. [9, 39], a self-organizing-map (SOM) neural network was used to realize formation transformation. The SOM input layer contains the positions in the target formation. The competition layer contains the actual positions of the AUVs, and the winning neuron is the AUV with the smallest Euclidean distance from the desired position. In this way, each AUV is assigned and moves to a desired position. However, the curvature constraint of the AUV is not considered in either of these papers. In addition, the process of calculating an SOM to allocate desired positions is centralized. In Ref. [40], the Hungarian method was applied to assign the desired AUV positions, whereby the cost of an AUV is represented by the Euclidean distance between the AUV and its desired position. A formation can be transformed into a horizontal line, vertical line, and a triangle. In Ref. [10], when searching for a target, the multi-AUV formation needs to transform into a circular shape around the target to hunt it, with several points generated uniformly around the target. Each AUV selects the nearest point and takes the shortest path to reach it.

3.2.2 Bottom control layer

The key task of the bottom control layer is designing a formation controller for the AUV. The parameters of the target formation are the reference inputs of the controller, and the formation state is adjusted according to the AUV's position, velocity, and other information until all the AUVs assemble into the target formation. Figure 5 shows a diagram of the control blocks in the formation controller.

Reference [34] developed a backstepping controller to achieve formation control using the Lyapunov function, which relies on sensor detection to maintain the formation. In Ref. [35], the backstepping control method was used to design a formation controller, and a neural network model was used to design a formation transformation method. In that method, the inputs of the network are the desired positions and obstacle positions, and the output is the AUV waypoint at the next transformation command. In Ref. [37], a state estimation-based controller was designed for follower AUVs in the formation transformation process. Each follower AUV determines its next waypoint according to its own current and historical positions and those of its leader. Reference [45] employed a fuzzy control strategy to transform the shape of the multi-AUV formation to avoid obstacles. Fuzzy rules were designed based on the automobile driving experience. The input of the fuzzy controller is the relative position relationship between the AUVs and obstacles, and the output is the AUV's turning angle.

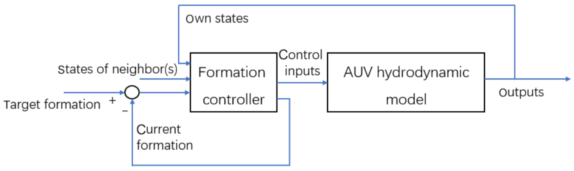


Fig. 5 Diagram of control blocks in the formation controller.

3.2.3 Summary

Table 4 gives a summary of some characteristics of the above studies, including the control strategies, control layer, and applicable environments of the methods. Most studies have considered formation transformation in environments in which there are obstacles and have applied the artificial potential field method to avoid them. In addition, a few studies have addressed formation transformation in 3D space.

Table 4 also gives the formation scale and shape before and after the transformation in the experiment. The formation scale in most studies is relatively small (the number of AUVs is not larger than 10), and the formation shapes considered are mostly conventional polygons, with the triangle and line more frequently considered.

4 Bibliometric Analysis

In this section, we perform a bibliometric analysis of the papers related to multi-AUV formation transformation

Table 4 Characteristics of the above studies. LF: leader-follower method; VS: virtual structure method; APF: artificial potential field method; BB: behavior-based method.

Reference	Control method	Layer	Environment	Scale	Current formation	Target formation
[7]	VS, APF	bottom control	obstacle, 2D	10	rectangle	triangle
[8]	APF	bottom control	obstacle free, 3D	30	different formation according to different movement of the trapped target	
[9]	VS, APF	planning	obstacle free, 2D	3	triangle	line
[10]	VS	planning	obstacle, 3D	7	herringbone	circle
[34]	LF	bottom control	obstacle free, 2D	3	specific method of formation transformation is not given	
[35]	LF, APF	bottom control	obstacle free, 2D	6	circle	rectangle
[36]	LF	bottom control	obstacle, 3D	7	herringbone	line
[37]	LF	bottom control	obstacle free, 2D	6	line	pentagon
[39]	VS, APF	planning	obstacle, 2D	3	triangle	line
[40]	VS	planning	obstacle, 2D	3	line / triangle	line / triangle
[42]	APF	bottom control	obstacle, 2D	6	triangle	smaller triangle
[45]	BB	bottom control	obstacle, 2D	5	herringbone	smaller herringbone
[47]	VS	planning	obstacle, 2D	4	quadrangle	line
[48]	BB	planning	obstacle free, 2D	120	line	circle
[49]	LF	bottom control	obstacle free, 2D	3	line	triangle

regarding the number of publications from different countries and institutions, the tasks performed, and environmental factors and constraints. Based on the results, we summarize the research status and future research directions of multi-AUV formation transformation.

Figures 6 and 7 show the number of publications from various countries and research institutions over the past decade, respectively. Among these countries, Chinese research institutions have published the most papers.

Representative Chinese institutions in this field include Harbin Engineering University, Shanghai Maritime University, and Shenyang Institute of Automation.

Figure 8 shows the number of publications related to formation transformation in different scenarios. Among them, the number of publications that consider obstacle avoidance is the largest, followed by that of publications on formation transformation during hunting tasks. Some documents do not state the reasons for formation transformation but simply focus on the transformation method used. Table 5 supplements the information in Fig. 8, listing the number of papers on formation transformation that consider different environmental factors and scenarios. Table 5 reveals that papers on obstacle avoidance, hunting, target search and tracking, and marine environment sampling investigated the influence of obstacles but considered only static obstacles, ignoring the influence of dynamic obstacles. Reference [12] proposes that a multi-AUV formation should transform into different formations at different water depths, but the influences of water quality and current on the formation transformation process are not considered.

Figure 9 shows the number of papers that consider different constraints (Table 3), from which we can see that all the papers consider the constraints of the communication topology connectivity and formation geometry, which are basic requirements for studying formation transformation. Some papers also consider the constraint of the distance between AUVs, and they mostly use the artificial potential field method to ensure that the distance between AUVs is not less than a given minimum value. Recent research on the autocorrelation constraints of the AUV is not comprehensive. A small number of studies have considered the curvature

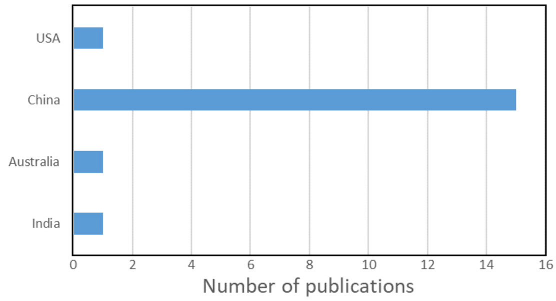


Fig. 6 Number of publications of various countries (2010–2020).

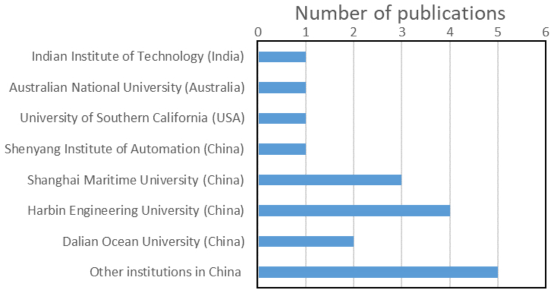


Fig. 7 Number of publications by different research institutions (2010–2020).

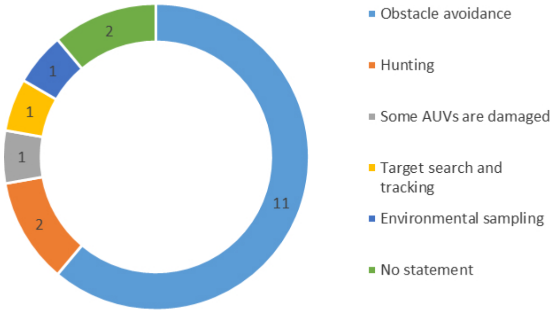


Fig. 8 Number of publications on formation transformation in different scenarios.

Table 5 Distribution of papers that consider different environmental factors and scenarios.

Scenario	Environmental element					
	Submergence depth	Water quality	Current	Static obstacles	Dynamic obstacles	No consideration
Obstacle avoidance	0	0	0	11	0	0
Hunting	0	0	0	1	0	1
Some AUVs are damaged	0	0	0	0	0	1
Target search and tracking	0	0	0	1	0	0
Environmental sampling	1	0	0	1	0	0
No statement	0	0	0	0	0	2

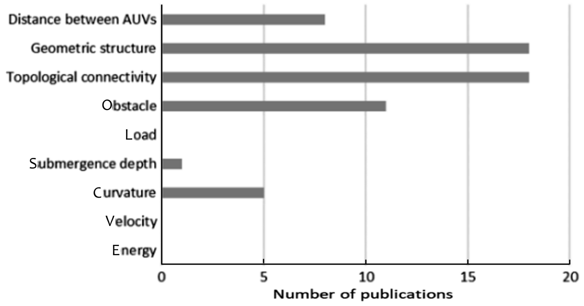


Fig. 9 Number of papers that consider different constraints.

constraints of the AUV. These papers mostly consider the method used in the bottom control layer and apply the AUV hydrodynamic model to design the controller.

5 Future Research Direction

Our investigation of the existing research reveals that many papers have reported the development of multi-AUV formation transformation methods that can be applied to various scenarios. However, some problems still need to be studied. In this section, we list some challenges associated with multi-AUV formation transformation and discuss future research directions.

5.1 Multi-UAV formation transformation in complex underwater environments

Most of the papers consider a relatively simple environment. The model of the underwater environment is generally simplified and cannot reflect the actual environmental complexity. Although some papers discuss the formation transformation method used in an environment with obstacles, most of them regard these obstacles as simple geometric shapes and ignore some important characteristics. In addition, they all consider static obstacles, whereas the underwater environment contains numerous dynamic obstacles. Most papers do not consider the influence of water depth, light field, water quality, and other factors that have an impact on the formation transformation process. In practice, however, the influence of these factors cannot be ignored. Therefore, the underwater environment should be modeled in greater detail to highlight its complexity. It is also necessary to design formation transformation methods that are suitable for more complex environments.

5.2 Transformation of large-scale multi-AUV formations

In most studies, the number of AUVs has varied from 2 to 10. When more AUVs are needed to perform more complex tasks, the effectiveness of these methods cannot be guaranteed. As the number of AUVs increases, the number of formation parameters greatly increases, which imposes a greater calculation burden. To address this problem, an imprecise formation can be used to describe the geometry. The communication topology of large-scale multi-AUV formations is more complex, and improving the stability of this topology is important for large-scale formations. Appropriate methods can be adopted to optimize the formation structure and improve the robustness of the communication topology. In addition, a decentralized architecture and distributed control should be adopted in large-scale formations to reduce their reliance on partial AUVs. In particular, with an increase in the formation scale, the distribution of AUVs may become much denser and even crowded, so the AUVs' motions can affect their neighbors by changing their common flow field, which merits further research. To consider multiple constraints, the complexity of formation transformation methods will increase, and the transformation time will become longer. As such, reducing the transformation time, optimizing the transformation process, and reducing the complexity of the methods will be the key problems in large-scale multi-AUV formation transformation.

To perform more complex tasks, AUVs with different abilities can be integrated into the same formation to improve efficiency.

5.3 Transformation without explicit communication

To date, most research on multi-AUV formation transformation has relied on explicit communication to transmit state and command information. However, the complex underwater environment often degrades the information quality of explicit communication. The topology established for explicit communication is easily damaged in confrontational environments. Using implicit communication to build a communication topology can improve this situation. By relying on sensors, AUVs can obtain information and adjust their own states. However, underwater environmental factors such as water depth, light field, water temperature, and water quality also affect the sensor performance. One basic method used to resolve this problem is to fuse and process the information obtained from multiple sensors to improve the effectiveness of the information. Another problem with implicit communication is that limited types of information can be detected. For instance, the position and velocity of an AUV and environmental information can be detected, but command information cannot be detected directly.

5.4 Optimal transformation process

Evaluation of the performance of formation transformation methods (cf. Q7) has seldom been considered in the literature. A better transformation process, e.g., in the sense of energy saving, can be obtained by simulating a school of fish and employing an artificial intelligence method such as reinforcement learning[50]. Through optimization or learning, the transformation time required can also be reduced. Moreover, recent research efforts have not yet identified a way to determine the limit of the realizable shapes of formations of a certain scale (cf. Q6), which is a fundamental issue in formation transformation and must be studied in depth.

6 Conclusion

In this paper, we reviewed the research on multi-AUV formation transformation conducted over the past decade and summarized some of its key problems. We also analyzed AUV motion models, formation structure, underwater environment, and constraints of transformation in detail. We then systematically classified representative studies on multi-AUV formation transformation with respect to the different formation control methods and layers used. We presented a bibliometric analysis of relevant publications with respect to their geographical distribution, formation tasks, and environmental factors and constraints. Finally, we highlighted the challenging problems and future research directions of multi-AUV formation transformation, including effective formation transformation in more complex underwater environments, large-scale multi-AUV formation transformation, formation transformation in the absence of explicit communication, and the optimal transformation process.

Acknowledgment

This work was co-supported by the National Outstanding Youth Talents Support Program (No. 61822304), the Basic Science Center Programs of NSFC (No. 62088101), the Peng Cheng Laboratory, the Consulting Research Project of the Chinese Academy of Engineering (No. 2019-XZ-7), the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (No. 61621063), and the Projects of Major International (Regional) Joint Research Program of NSFC (No. 61720106011).

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