Yan *et al*. *Intell Robot* 2023;3(1):1-22
DOI: 10.20517/ir.2023.01

Intelligence & Robotics

Review

Open Access

Formation control of multiple autonomous underwater vehicles: a review

Tao Yan[1], **Zhe Xu**[1], **Simon X. Yang**[1], **S. Andrew Gadsden**[2]

[1]School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada.
[2]Department of Mechanical Engineering, McMaster University, Hamilton, Ontario L8S 4L8, Canada.

Correspondence to: Prof. Simon X. Yang, School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada. E-mail: syang@uoguelph.ca

How to cite this article: Yan T, Xu Z, Yang SX, Gadsden SA. Formation control of multiple autonomous underwater vehicles: a review. *Intell Robot* 2023;3(1):1-22. http://dx.doi.org/10.20517/ir.2023.01

Received: 24 Sep 2022 **First Decision:** 9 Nov 2022 **Revised:** 23 Nov 2022 **Accepted:** 19 Dec 2022 **Published:** 14 Jan 2023

Academic Editor: Chen Peng **Copy Editor:** Yinyin Han **Production Editor:** Yinyin Han

Abstract

This paper presents a comprehensive overview of recent developments in formation control of multiple autonomous underwater vehicles (AUVs). Several commonly used structures and approaches for formation coordination are listed, and the advantages and deficiencies of each method are discussed. The difficulties confronted in synthesis of a practical AUVs formation system are clarified and analyzed in terms of the characteristic of AUVs, adverse underwater environments, and communication constraints. The state-of-the-art solutions available for addressing these challenges are reviewed comprehensively. Based on that, a brief discussion is made, and a list of promising future work is pointed out, which aims to be helpful for the further promotion of AUVs formation applications.

Keywords: Autonomous underwater vehicles (AUVs), formation control, challenges and difficulties, state-of-the-art solutions

1. INTRODUCTION

Unmanned underwater vehicles (UUVs) as effective devices have played a key role in exploration and exploitation of marine resources for human beings since about 1960s. In particular, remotely operated vehicles (ROVs)[1,2] as the typical UUVs, tethered with a cable used for data transmission and power supply, have been widely applied in the oil and gas industry and other common fields where underwater inspection, maintenance and intervention necessitate. Nonetheless, such a vehicle does not seem to be cost-effective, since in order to execute missions, an associated support vessel and operators are always needed. While there has been a so-called fully autonomous ROV recently without requiring any intervention from operators, the tether or supply ship can still not be removed, which sometimes yields the most expenditure[3,4]. To overcome this drawback while improving working performance, autonomous underwater vehicles (AUVs) have received increasing attention in the past few decades from both industry and academia. As an obvious distinction from the ROVs, AUVs get rid of the tethers, operate automatically for the assigned missions, and require neither human intervention nor support ships. Therefore, the cost of each operation can be reduced to a great extent, and moreover, due to the characteristics mentioned, AUVs can even be adopted to access restrictive areas, e.g., shallow water or under-ice areas. The growing applications in practice can even be found as the efficient alternative to ROVs[5–10]; for example, they are used frequently to perform various survey and inspection tasks in the deep sea, such as hydrographic survey (i.e., positioning or locating the underwater surroundings), submarine cable inspection, oil and gas pipeline inspection and maintenance, etc. Besides, such mechatronic systems are also helpful for the science purpose; that is, a great many marine organisms can be discovered and identified with the assistance of high-quality cameras, and many ancient shipwrecks can be surveyed and excavated using these effective tools. In addition to that, AUVs have even been employed by several navies for military use, such as mine neutralization, intelligence gathering, reconnaissance or even nuclear bomb searching, etc.

However, as the complexity of missions grows, it is becoming nearly impossible for a single AUV system to attain a satisfactory result. As a consequence, along with the recent advances of the multi-agent systems theory, the developments of multiple autonomous underwater vehicle systems have received much attention in communities of control and ocean engineering over the past few decades[11,12]. It is natural that a vast amount of difficulties can be handled efficiently by employing a group of AUVs. Besides that, such a multi-agent system has many beneficial inherent features, including high degree of flexibility, ease of extension and maintenance, and better robustness against perturbations and failures[13,14], etc.

The research efforts on a swarm of AUVs are mainly focused on designing efficient protocols and algorithms such that some useful collective behaviors among individuals can emerge, which is roughly categorized into problems such as formation control, flocking, hunting, pursuit-evasion[15–20], etc. It is observed from literature review that formation control of AUVs fleet has attracted the most attention among those research topics, due to its considerable potential in practical maritime operations, which also motivates this brief survey. Notice that there are several definitions of formation control found in the literature[21]. For example, some definitions are either forcing the constraints on relative positions of agents or just simply demand speed synchronization of each individual (without the need to maintain a specific distance from each other). In this article, formation control is referred to as designing controllers for a fleet of AUVs so that some prescribed formation shapes can be formed and kept, and meanwhile, the velocities of each AUV in the group are agreed to move along with a desired route as a whole. In short, formation control attempts to control the relative distance and bearing between vehicles while maneuvering together. It is worth noting that AUV formation is totally different from the problem of AUV-assisted underwater acoustic networks (UANs)[22,23], while they both seek to employ multiple AUVs to construct a communication network. In vehicle assisted UANs, AUVs play a role in shortening the distance of information connection from the stationary nodes to the surface vessels or buoy beacons. In such a way, the communication quality can be improved considerably through AUV relay. Nonetheless, in this process, the shapes of the AUVs fleet are not necessarily constrained, and indeed people are concerned more about the AUVs path planning or task assignment so as to obtain the shortest routes with relatively lower energy consumption[24]. In contrast, as mentioned earlier, the AUVs formation control is mainly focusing on the design of efficient and robust control techniques for AUVs in order to strictly meet the prescribed formation constraints. The recent advances in sensor technologies and algorithms used for underwater localization and navigation can be found in the survey papers[25,26], which also serve as critical factors contributing to better formation control performance. This paper is mainly from a control point of view to examine the AUV formation applications. In addition, it is worth noting that there exist three types of AUVs, i.e., fish-like AUV, underwater glider, and torpedo-like AUV. Due to a balanced performance of torpedo-like AUV as reported in literature[27], in this brief we are specifically concerned with the formation control of this type of AUV. For more details on performance comparison among three types of AUVs, the readers of interest are referred to the paper[27]. In what follows, for convenience, the term AUV is referred to as the torpedo-like AUV.

In fact, it is not easy to develop high-performance formation controllers for a group of AUVs[5–7]. Major technical problems may arise from the following several aspects. First, it is notorious that the dynamics of AUVs are highly nonlinear with 6 degrees of freedom (DOF), but not fully actuated; that is, the control actions are not directly applied in the sway and heave motion directions. Besides, subject to the severe effects of hydrodynamics, a set of hydro-related plant parameters in AUV dynamic model are always time-varying, and furthermore, the ocean waves and currents have significant impacts on the dynamics of AUVs as well. Those mentioned factors even make the motion control of a single AUV fairly challenging[28]. More importantly, to control the formation of AUVs fleet, it is imperative to establish a communication network to exchange information between the vehicles. Nevertheless, due to the underwater environments, radio frequency and optical based communication technologies are usually inefficient, when the communication zone becomes broad, which is the case in AUVs formation in order to attain maximum coverage. In such a case, acoustic-based technology is regarded as the most suitable way to provide communication support for AUVs formation applications[27,29,30]. As a result, the communication constraints induced, e.g., low data rate, high propagation delays, path loss, noises, Doppler effect, etc., cannot be neglected. There have been a variety of surveys discussing and summarizing the formation control techniques available for multi-agent systems, especially including integrator-modeled systems[11,31], unmanned ground vehicles (UGVs)[31–33], unmanned aerial vehicles (UAVs)[34–37], unmanned spacecraft[38,39]. It is clear that due to the distinct applications as well as the characteristics, the technical challenges encountered in these systems may have an apparent difference from the autonomous underwater vehicles. For example, as a stark contrast, the communication channels for formation control of UGVs, UAVs and spacecraft are much better than those of AUVs, since for the former, the base stations and satellites can offer a stable high data rate and lower transmit errors. Consequently, the communication constraints may not be considered critical or pressing for such systems in order to achieve a high-precision formation performance. In addition, most of the existing available surveys on AUVs formation are mainly concerned with the motion control techniques and formation coordination strategies[29,40–43], but with limited focuses on communication problems which are, as mentioned, vital for the AUVs to reach a robust formation performance in underwater environments.

In light of the aforementioned observations, we believe that it is timely and helpful to present a brief overview of recent advances in AUVs formation control techniques that includes, particularly, a sufficient survey in handling underwater communication constraints. Notice also that due to the vast amount of the literature, it would be intractable to extensively review the existing results. We are thus concentrating on the major technical challenges and practical issues that significantly affect the formation control quality. In particular, we discuss the influence arising from the underwater communication constraints, which may deteriorate the formation performance in practice, but not well-studied in previous surveys. The contributions of this paper are listed: (1) Several popular formation coordination structures and approaches used for AUVs formation are presented, and their advantages and drawbacks with respect to the implementation, analysis, robustness and flexibility are discussed in-depth; (2) The difficulties in the development of a practical AUVs formation system are classified and analyzed in terms of the characteristic of AUVs, adverse underwater conditions, and communication constraints. Based on that, a comprehensive literature review of recent advances to handle these challenges is conducted; (3) According to the results of the survey, a summary is made, and several promising research directions are pointed out, which may be beneficial to promote the development of this field.

The rest of the paper is arranged in the following. Section 2 provides some preliminaries on AUVs formation control systems. Several widely used formation coordinating structures and approaches are presented in Section 3. The technical problems and practical considerations in applications are clarified, and the existing research solutions are reviewed extensively in Section 4. Section 5 gives a summary and points out some valuable future works. Section 6 concludes the paper.

2. PRELIMINARY

In this section, some preliminaries are presented. Particularly, graph theory is introduced, which serves as a useful tool to represent and analyze the interaction of AUV networks. Then, the mathematical model of the AUVs is given to describe the motion of each autonomous underwater vehicle.

2.1. Basic knowledge on graph theory

To analyze the properties of a AUVs formation system, graph theory can be used as a useful tool. This subsection aims to introduce some fundamental concepts in graph theory. The graph, denoted by a triple $G = \{V, E, A\}$, can be used to represent the communication topology among a AUVs fleet, including the vertex set $V = \{v_1, v_2, \ldots, v_N\}$, edge set $E \subseteq V \times V$ and weighted adjacency matrix $A = \left[a_{ij}\right] \in \mathbb{R}^{\mathrm{N} \times \mathrm{N}}$. In particular, the element v_i in the vertex set V, termed a node, represents the AUV i in the group, where i belongs to an accountable index set $\Gamma = \{1, \ldots, N\}$. The element $\left(v_i, v_j\right)$ in the edge set E describes the interaction between AUVs i and j, and associated with weights $a_{ij} = a_{ji} > 0$, which are the entries of adjacency matrix A. In such a case, we call AUV j a neighbor of AUV i, and all the neighbors of AUV i can be described by the set $N_i = \left\{j | \left(v_i, v_j\right) \in E\right\}$. If there is no connection between AUVs i and j, then let $a_{ij} = a_{ji} = 0$ and $\left(v_i, v_j\right)$ is not the element of E. We may further define $a_{ii} = 0$ for all $i \in \Gamma$, and out-degree of the node i as $d_i = \sum_{j \in N_i} a_{ij}$, after which the degree matrix and the Laplacian matrix of the graph G can then be defined as $D = \operatorname{diag}\{d_1, \ldots, d_N\} \in \mathbb{R}^{\mathrm{N} \times \mathrm{N}}$ and $L = D - A$, respectively.

In addition, a path in graph is defined by a sequence that contains a set of successive adjacent nodes, starting from the initial node and ending at the final node. If there exists at least one path between any two nodes in a graph G, then, say, graph G is connected. Furthermore, in order to make the AUVs fleet move along with a desired path as a whole, a reference trajectory must be defined ahead of time. Thus, the availability of the information of reference trajectory for i-th AUV is characterized by a parameter b_i; that is, if AUV i is permitted to access this information, then $b_i > 0$; otherwise, $b_i = 0$, and define $B = \operatorname{diag}\{b_1, \ldots, b_N\}$. Based on that, we may have the following important lemma, which is useful to help analyze the stability of AUVs formation systems based on the graph theory.

Lemma 1 *For the considered AUVs formation control network, described by graph G, if G is connected and there is at least one AUV able to access the information of the reference trajectory, i.e., the elements of B are not all equal to zero, then the matrix L + B is positive definite.*

2.2. Mathematical models of AUVs

The kinematics of each AUV is described as[28]

$$
\begin{aligned}
\dot{x}_i &= \cos\theta_i \cos\psi_i u_i - \sin\psi_i v_i + \sin\theta_i \cos\psi_i w_i, \\
\dot{y}_i &= \cos\theta_i \sin\psi_i u_i + \cos\psi_i v_i + \sin\theta_i \sin\psi_i w_i, \\
\dot{z}_i &= -\sin\theta_i u_i + \cos\theta_i w_i, \\
\dot{\theta}_i &= q_i, \\
\dot{\psi}_i &= \frac{1}{\cos\theta_i} r_i,
\end{aligned}
\tag{1}
$$

where (x_i, y_i, z_i) and (θ_i, ψ_i) are the position and orientation of the i-th vehicle ($i \in \Gamma$), respectively, expressed in the earth-fixed frame $E^{\mathrm{I}} = \left\{e_o^{\mathrm{I}}, e_x^{\mathrm{I}}, e_y^{\mathrm{I}}, e_z^{\mathrm{I}}\right\}$, and (u_i, v_i, w_i) and (q_i, r_i) are the linear and angular velocities

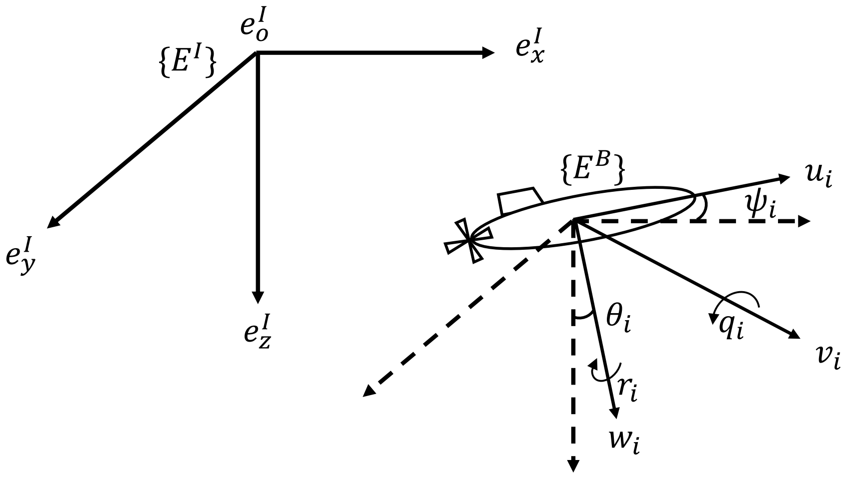

Figure 1. Earth-fixed frame and body-fixed frame systems of i-th AUV

of the i-th vehicle, respectively, which is expressed in the body-fixed frame $E^{\mathrm{B}} = \left\{e^{\mathrm{B}}_{o,i}, e^{\mathrm{B}}_{x,i}, e^{\mathrm{B}}_{y,i}, e^{\mathrm{B}}_{z,i}\right\}$, as shown in Figure 1.

The dynamics of the i-th vehicle is modeled by

$$\begin{aligned}
m_{i1}\dot{u}_i &= m_{i2}v_i r_i - m_{i3}w_i q_i - \beta_{ui}u_i + \tau_{i1} + d_{i1},\\
m_{i2}\dot{v}_i &= -m_{i1}u_i r_i - \beta_{vi}v_i + d_{i2},\\
m_{i3}\dot{w}_i &= m_{i1}u_i q_i - \beta_{wi}w_i + d_{i3},\\
m_{i4}\dot{q}_i &= (m_{i3} - m_{i1})\,u_i w_i - \beta_{qi}q_i - \beta_{bi}\sin\theta_i + \tau_{i2} + d_{i4},\\
m_{i5}\dot{r}_i &= (m_{i1} - m_{i2})\,u_i v_i - \beta_{ri}r_i + \tau_{i3} + d_{i5},
\end{aligned} \tag{2}$$

where $m_{i1} = m_i - \beta_{\dot{u}i}$, $m_{i2} = m_i - \beta_{\dot{v}i}$, $m_{i3} = m_i - \beta_{\dot{w}i}$, $m_{i4} = I_{yi} - \beta_{\dot{q}i}$ and $m_{i5} = I_{zi} - \beta_{\dot{r}i}$; m_i is the mass of the i-th vehicle; I_{yi} and I_{zi} are the moments of inertia around the axes of $e^{\mathrm{B}}_{y,i}$ and $e^{\mathrm{B}}_{z,i}$, respectively; $\beta_{(\cdot)}$ is set of hydrodynamic related terms associated with the i-th vehicle, $\tau_i = [\tau_{i1}, \tau_{i2}, \tau_{i3}]^{\mathrm{T}} \in \mathbb{R}^3$ is the control input, and $d_i = [d_{i1}, d_{i2}, d_{i3}, d_{i4}, d_{i5}]^{\mathrm{T}} \in \mathbb{R}^5$ is the disturbance acting on the i-th vehicle.

Remark 1 *It is worthwhile noting that the complete motion of the equation of an AUV is of 6 DOF, but, as we surveyed, almost all of the literature studying 3-dimensional (3D) formation applications employ the AUV model, as presented in Equation (1) and Equation (2), with 5 DOF. This relies on the fact that for an AUV formation fleet, the rotational motion around* $e^{\mathrm{B}}_{x,i}$ *axis, i.e., roll motion, sometimes is not required in many practical AUV maneuvering, and hence the equation governing the roll motion is intentionally omitted, which does not cause loss of the practicality. Indeed, it is easy to check that the roll motion is passively bounded*[28]*. Particularly, its impacts on the other DOF can be treated as unmodeled dynamics and handled effectively by some disturbance rejection techniques.*

Remark 2 *It is clear that the dynamics of AUVs are highly nonlinear and underactuated as in Equation (2); in other words, the sway and heave velocities, i.e.,* v_i *and* w_i*, are not fully actuated and there are no actual control actions allowed to be applied. In the sequel, this underactuation feature will be demonstrated as a major challenge to designing high-performance formation controllers for AUVs. In addition, besides the environmental disturbances described by* d_i*, as observed in Equation (2), there are many system parameters subject to the perturbation due to the effect of hydrodynamics, which is characterized by the time-varying parameters* $\beta_{(\cdot)}$*. Such uncertainties in the dynamic model of AUVs give rise to another significant difficulty for the formation control design. Furthermore, the angle of* θ_i *is constrained and not allowed to take values at* $\pm\pi/2$ *in order to avoid the singularities, which* *should be guaranteed by the formation controller. Therefore, from the control point of view, addressing such a system continues to be challenging.*

2.3. Problem statement

This subsection aims to formulate the considered formation control problem of a fleet of AUVs. As mentioned earlier, one of the requirements of formation control is to drive the AUVs to form a prescribed static or time-varying geometric shape and maintain it. Typically, the expected geometric pattern can be determined by the appropriate assignments of the relative positions between vehicles, denoting as $\Delta_{ij} = \left[\delta_{x,ij}, \delta_{y,ij}, \delta_{z,ij}, \delta_{\theta,ij}, \delta_{\psi,ij}\right]^{\mathrm{T}}$ for AUV i ($i \in \Gamma$) and its neighboring nodes $j \in N_i$. To this end, the formation control is cast to the problem of controlling relative positions and orientations of vehicles with respect to their neighbors so that Δ_{ij} can be achieved as time tends to infinity, and particularly these desired relative poses could even be set to be time-varying as necessary. Another practical requirement is that it is most desirable for an AUVs fleet in applications to track a reference trajectory as a group, in which case not only the positions, but also the velocities of the vehicles in the fleet are needed to be in consensus; that is, $(\dot{x}_i, \dot{y}_i, \dot{z}_i)$ converges to a common reference speed $(\dot{x}^d, \dot{y}^d, \dot{z}^d)$, as $t \longrightarrow +\infty$. Such an objective is also referred to as the problem of formation tracking control in the literature.

In short, the formation control objective can be summarized as designing controllers for AUVs such that a set of desired relative positions and orientations, i.e., Δ_{ij} $(i, j \in \Gamma)$, can be achieved and maintained while the AUVs fleet tracks a common reference trajectory, moving in the same speed together.

3. AUV FORMATION CONTROL PROTOCOLS

In order to achieve the preceding formation objective, an appropriate formation control protocol is a must to coordinate the motions of AUVs efficiently. In general, multi-agent coordinating strategies can be roughly categorized into two forms depending on the information used, i.e., centralized coordination and decentralized coordination[11,31]. In centralized form, the control commands or control actions of each AUV are planned through a central control procedure which is allowed access to the global information of the whole formation system. On the contrary, in a decentralized structure, there is no such a controller planning actions for every AUV in the group, and instead, AUVs make their own decisions based on their local information accessed. In fact, on the basis of an extensive review, there are few research efforts made to design centralized coordination protocols for AUVs formation applications, which owes to the fact that each AUV employed has sufficient capabilities to sense the surroundings, plan its control actions accordingly and communicate with neighbors.

Based on this observation, we are mainly concerned with the approaches adopting a decentralized coordinating control structure, which includes leader-following structure, virtual structure, behavior-based approach, artificial potential field approach, and other common structures.

3.1. Leader-following structure

Leader-following structure is one of the most popular schemes used for the formation control of multiple agent systems because of its straightforward descriptions[11]. In such a scheme, one or several agents are selected as the leaders, and the rest of the agents are grouped into followers, as depicted in Figure 2. The desired reference signal is merely known to the leaders, and in conventional leader-following structure, the goal of the leaders is simply to track this prescribed reference and there is no explicit interaction between their following agents. The sole goal of the remainders is aimed to keep the desired relative pose (i.e., position and heading) with respect to their leading agents. As such, the formation control objective, as stated in section 2.3. can be achieved if each vehicle's goal is reached. The major advantages of such a method are that it is easy to be implemented and fairly flexible to add or remove vehicles in the fleet; besides, since there are no direct interactions between neighboring vehicles, the stability of the whole formation system can be easily analyzed based on the graph

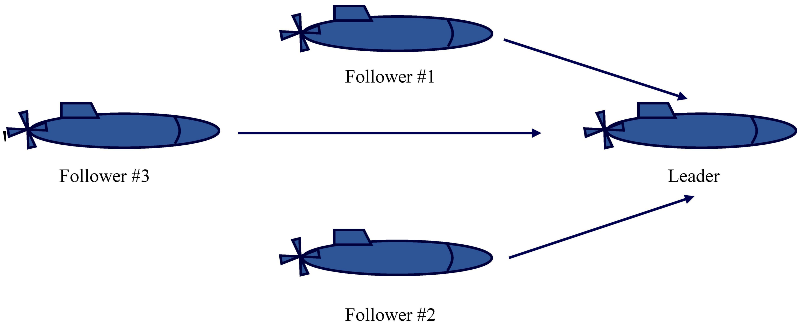

Figure 2. A typical topology of leader-following structure.

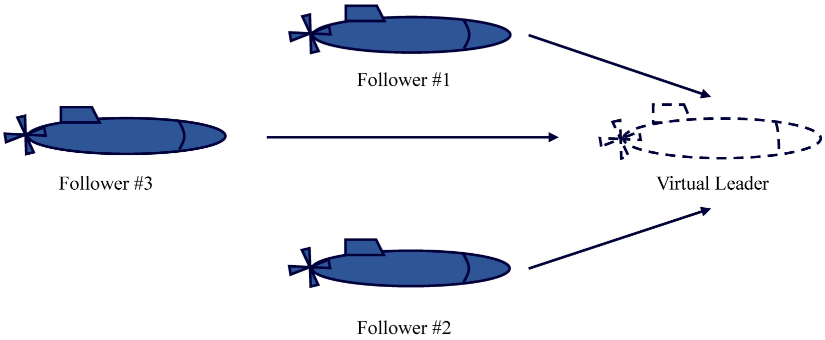

Figure 3. A typical topology of virtual leader structure.

theory, as presented in section 2.1. Because of those nice features, there is a great amount of literature on AUV formation control adopting the leader-following structure[44–48].

Such an approach, however, suffers from a major defect that the performance of the overall formation system depends highly on the behavior of the leaders and the quality of the communication. In other words, once the lead agents or communication network fail to work as usual due to unpredictable faults, which is often the case in underwater environments, the entire formation system may be disabled. To overcome this issue and improve the robustness of the leader-following approach, a virtual leader based method is proposed, in which there are no physical vehicles employed to lead the group and, therefore, the above-mentioned issue can be appropriately addressed[49–52]. A typical virtual leader based formation structure can be referred to the Figure 3. Another critical consideration regarding this type of structure is that it is always assumed that every vehicle in the group is permitted to obtain the trajectory information of the virtual leaders, which is a strong assumption and may not be fulfilled in many realistic applications.

3.2. Virtual structure approaches

Similar to the virtual leader approach, virtual structure coordination is another common method used to coordinate the multi-agent formation, which was first reported in[53,54] to address the cooperative control of multiple mobile robots. In this method, a set of virtual points are defined corresponding to each vehicle, which is determined by the desired formation configuration as well as the trajectory to be tracked. Since each vehicle is assigned its own reference point, the formation tracking problem is then converted into the tracking control problem associated, the goal of which is to drive the vehicles to minimize the errors between their actual positions and desired ones. A typical realization of such an approach is illustrated in Figure 4. Due to the fact that such a method is also straightforward and simple to analyze and realize, there have been many results reported to date based on this method to achieve the formation control requirements[54–59].

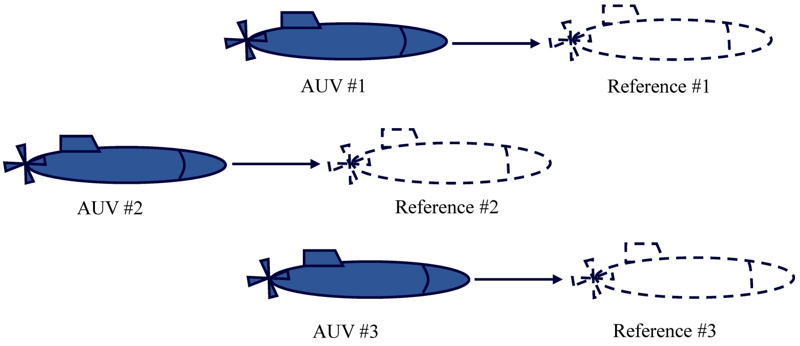

Figure 4. A typical topology of virtual structure approach.

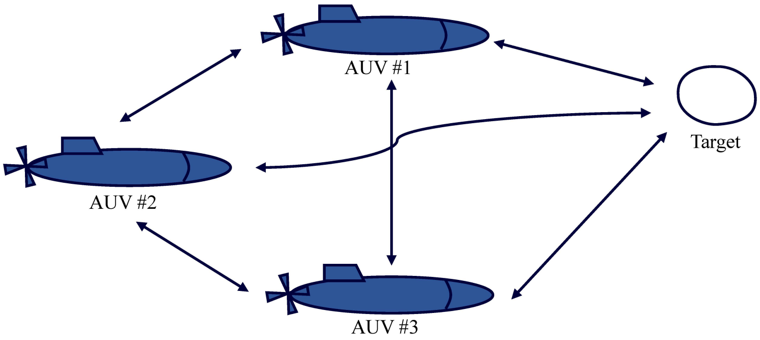

Figure 5. A typical topology of behavior-based approach.

The main drawbacks of the virtual structure approach may lie in several aspects: (1) Like the virtual leader approach, this method relies closely on the desired reference trajectories, which appears to be unrealistic in many practical scenarios; (2) It is not easy to expand the AUV formation, since the desired virtual reference points are designed in advance based on the prescribed formation pattern; (3) Due to the lack of information exchanges between the neighboring vehicles, there is no cooperation occurred in the formation system, which degrades the coordination performance.

3.3. Behavior-based approaches

Different from the above two methods, as shown in Figure 5, there exists an explicit mutual communication in formation systems synthesized using the behavior-based coordination approach. Instead of directly prescribing *a priori* reference trajectories, in behavior-based approach, each vehicle in the group makes its own decisions based on the local information (e.g., its own states, surroundings, and neighbors' states) and the goals predefined. The goals usually include target reaching, collision or obstacle avoidance, distance maintaining, etc. Particularly, the overall control actions of the vehicles are then generated by a weighted combination of achieving these different goals. Due to the multi-objective and distributed features, behavior-based approach has attracted extensive attention over the past few decades in the research areas of multi-agent cooperation and coordination[60–64].

Although the behavior-based scheme is turned out to be able to achieve multiple objectives and is merely dependent on the limited local information to calculate control activities, it is hard to analyze the stability properties of the overall formation system based on such a method when more vehicles and behaviors are involved. This restricts its practical applications greatly.

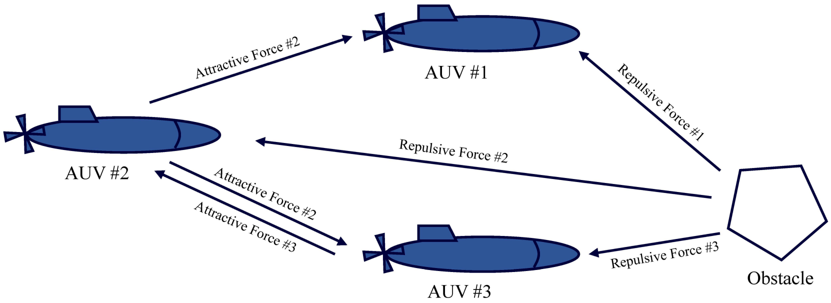

Figure 6. A typical topology of APF-based approach.

3.4. Artificial potential field approaches

Artificial potential field (APF) approach is first invented by Khatib[65] in order to design an algorithm to generate an obstacle-free route for manipulator and mobile robot path planning. The main feature of the method is that a series of artificial potential functions are defined intentionally with the purpose of reaching the target and meanwhile avoiding obstacles. Analogous to the potential energy in physics, the APF functions defined can generate corresponding potential forces as well. Typically, there are two types of APF functions involved: One aims to generate attractive potential forces to bring the vehicles to the targets, and another attempts to yield the repulsive potential forces to make the vehicles keep away from the obstacles, which is shown in Figure 6. As a consequence, under both the attractive and repulsive forces, the prescribed objective can be attained. Inspired by such a formulation of clear physical significance, APF approach is also introduced in various multi-agent systems to help organize the cooperation and coordination[66–72].

Similar to the behavior-based approach, it is relatively easy for the APF approach to synthesize distributed controllers that achieve multiple goals depending only on the local information. However, one major drawback is that it has the chance to trap into points at which the resulting net force applied on vehicles is zero, which is also known as the issue of ”local minima”. Likewise, the stability analysis of APF based multi-agent systems is not easy as well, compared to the leader-follower structure and virtual structure approaches, when the scale of the group grows larger.

3.5. Other approaches

By a comprehensive literature review, there are some other commonly used approaches to achieving the multi-agent cooperation and coordination, while these kinds of schemes can be, in some sense, regarded as variants of those already presented. For example, the so-called formation reference point (FRP) method is actually a type of virtual leader method, in which a reference point is defined and parameterized with desired velocity profile, and then the control objective of vehicles in the group is simply to maintain a specific distance and bearing with respect to the reference point[73,74]. Like the conventional virtual leader method, there are no explicit interactions took place between neighboring vehicles.

In the field of multi-agent coordination, there exist a fundamental problem, termed consensus problem, which characterizes how the inter-agent cooperation can be emergent by merely using the local information (i.e., interacting with neighbors)[75]. Specifically speaking, it is possible that the state of the entire multi-agent system can be ultimately in consensus; that is, each agent's state converges to the same equilibrium point under a proper local control law that is designed only based on the neighboring information. Moreover, such a problem can be well formulated and tackled by the graph theory, as mentioned in section 2.1, including the basic issues such as the existence of solutions, stability and robustness properties of multi-agent systems. For this reason, a vital amount of related research results on networked multi-agent systems coordination based on consensus approach are reported both in theoretical and practical dimensions[31,76–81]. Such a problem is then extended to the case of formation control design, where a virtual leader is introduced to guide the vehicle group

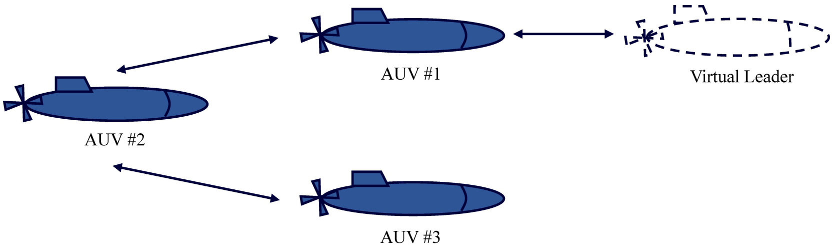

Figure 7. A typical topology of consensus-based approach.

to move along with a reference trajectory together, and meanwhile, the formation is formed by the exchange of information between neighbors[82–84]. A typical communication topology of consensus-based formation control is illustrated in Figure 7.

It should be noted that in stark contrast with the conventional virtual leader structure, there exists local information flow in the consensus based approach, and more importantly, it is not necessary that all members in the group have access to the information of reference trajectory[85–87]. It is, in effect, the sole condition that the graph associated has a spanning tree[11]. Those mentioned features seemingly make the consensus based method more practical and beneficial for real-word applications among various formation control methods. While such a method has attracted much attention in the studies of groups of unmanned ground vehicles[88–92], unmanned aerial vehicles[93–98], and spacecraft[99–102], there is still a lack of sufficient research efforts to apply consensus based approach to the multi-AUV formation where more practical challenges associated should be addressed further, most of which will be discussed in what follows.

4. PRACTICAL ISSUES AND CHALLENGES IN AUV FORMATION CONTROL

This section discusses the major technical challenges and several practical issues encountered in the synthesis of AUVs formation control systems in terms of motion control of AUVs, addressing the adverse underwater conditions and communication constraints. A great variety of existing available results to tackle these difficulties are reviewed comprehensively, and the features of each type of method are pointed out.

4.1. Nonlinear constrained dynamics of AUVs

As mentioned earlier, different from the general multi-agent systems[11] where a point-mass model is typically used to describe the motion of agents, the governing equations of AUVs are much more complicated as explained in Remark2, including nonlinearity, underactuation and system constraints. As a result, such systems may suffer from some extra design complexities in respect of motion control. To deal with the nonlinearity, employing an approximated model is a likely choice by linearizing the nonlinear model at a specific operating point, and then linear control theory can be used to design the motion controller for AUVs. Based on this idea, the authors[103] proposed a nonlinear gain scheduling controller for heading control of AUVs in the horizontal plane. In this study, a finite number of linear static feedback controllers were derived at distinct speed conditions, after which the parameters of the controller were interpolated upon speed. The resulting scheduled controller was designed using the D-methodology[104] to guarantee the stability of the overall closed-loop system. To obtain an optimal control performance with respect to a quadratic-type objective, a linear-quadratic regulator (LQR) algorithm was implemented[105], and an optimal state feedback gain was figured out to regulate the AUVs' depth as well as stabilize the roll and pitch angles. In order to account for the approximating errors and the time-varying environmental conditions, a robust H_∞ based depth control was proposed[106], in which the aim of the controller is to minimize the cost function under the maximum effects of the parametric perturbations, and the resulting robust performance is verified by simulation.

Another class of optimization-based control methods, termed model predictive control (MPC), is inherently effective in handling internal uncertainties. Due to the preceding horizon formulation, an online optimization mechanism is enabled in MPC using real-time state feedback against the potential modeling errors. Furthermore, owing to a shortened horizon employed in optimization, such a method is also allowed to handle the state and input constraints, which is a very beneficial and useful feature in designing practical controllers as nearly all of the physical systems are subject to actuation saturation. By means of the MPC policy, the authors[107] studied three-dimension (3D) underwater tracking control of a fully-actuated AUV with the practical constraints in both state and input, and the simulation results verified the satisfactory performance in the presence of various disturbances. In underwater conditions, the measurement noises may be another non-negligible factor affecting the control performance. To this end, linear quadratic Gaussian (LQG) control, integrated with the Kalman filtering (KF) technique, serves as an efficient optimal control strategy to ensure that the controlled system operates at the optimum status in the sense of variance minimization[108]. Recently, a model predictive tracking controller was combined with an extended state based Kalman filter for a constrained remotely operated underwater vehicle in order to achieve a high-precision tracking performance, while the system nominal model is uncertain and subject to both sensor noises and external disturbances[109].

However, most of the aforementioned approaches are designed based on a linearized model at some specific operating points, which necessitate assumptions that the AUVs move at a relatively low speed and the impacts of disturbances, caused by the ocean waves and currents, are much limited such that the locally stable results can be obtained. Such a hypothesis may be quite conservative and, in effect, not always hold in practical situations. In view of that, nonlinear control techniques have been the research focal point over past decades to help develop high-performance motion controllers for AUVs with global stability guarantee. The researchers[110] proposed a nonlinear tracking controller for a remotely controlled AUV based on the feedback linearization technique, under which the resulting system becomes a decoupled linear system, and furthermore, an optimal error correcting term is added in the feedback loop, based on LQR approach, to compensate the uncertainty. To derive adaptive formation tracking controllers for a group of underactuated AUVs in a horizontal plane, the backstepping design procedure and neural network technique are used[46]. The resulting nonlinear formation controllers developed for each AUV are based on a virtual leader structure without knowledge of the leader's velocity and dynamics, and the overall AUVs formation is proved to be uniformly ultimately bounded stable using the Lyapunov stability theory. Due to the obvious benefits of MPC approach in handling systems constraints, a nonlinear MPC controller was presented for the tracking control of an AUV in 2-dimension (2D) case[111,112], where an auxiliary nonlinear control law is proposed using the backstepping-based Lyapunov synthesis, and as a result, the linearization procedure can be avoided for standard MPC design, which improves the region of attraction of resulting system greatly. Furthermore, the resulting Lyapunov-based MPC is guaranteed with properties of iterative feasibility and stability. Following the same ideas, the authors[113] developed a leader-follower based receding horizon kinematic controller for formation control of a constrained underactuated AUV. Taking into consideration the uncertainties in modeling, the authors combined the extended state observer (ESO) with nonlinear MPC to deal with the formation tracking of AUVs[114].

Another class of important methods to address complex systems is intelligent control, including fuzzy logic control, neural network control, and data-driven control (sometimes in the literature also called machine learning-based control), etc. For instance, the authors[115] developed a nonlinear fuzzy logic based proportional-integral-derivative (PID) controller to regulate an AUV's heading and depth, and in particular, Mamdani fuzzy rules are used to tune the control gains of PID adaptively to address the nonlinearity and uncertainties in AUV modeling. As well, to address a similar issue, 3D path following of an underactuated AUV is investigated using fuzzy logic based backstepping controller[116]. It is worth noting that AUVs path following problem is slightly different from the tracking problem, while they are both expected to follow a desired route. The former does not impose a strict temporal constraint on the reference trajectory. Thus, an extra degree of freedom in the speed of the trajectory can be exploited to design controllers, which could be practical in some applications[6].

To handle the nonlinear and unknown dynamics of AUVs, a data-driven model-free predictive approach[117] was proposed for the accurate trajectory tracking control, in which the authors suppose that both parameters and order of the plant are unavailable to control design. To address a similar problem, an adaptive line of sight (LOS) guided reinforcement learning approach based on the long short-term memory (LSTM) neural network model was devised[118]. Considering the unknown nonlinearity in AUV dynamic model, underactuation and input limitation, the author[119] designed a neural network based robust formation controller using virtual structure for a group of underactuated AUVs with actuation saturation, and furthermore, rigorous stability analysis was provided.

4.2. Adverse underwater environments

In addition to the nonlinear, uncertain and underactuated characteristics of the AUVs dynamics as discussed above, the complicated underwater conditions (e.g., marine disturbances, hydrodynamic effects, unpredictable static or dynamic obstacles) may also pose a great difficulty in AUVs formation design. In the preceding discussions, we have already mentioned numerous methods to address the uncertainties in AUV dynamic model, most of which adopt an adaptive idea, e.g., adaptive control methods, data-driven methods, neural network-based methods, etc., to estimate parameters (either control gains or model-related parameters) in a real-time manner based on the measured data. This class of methods, although superior, is basically suitable for the case when the structure of the uncertainties is known, but the associated parameters are required to be estimated. On the other hand, due to the integration with online parameter estimation, most existing adaptive approaches result in a nonlinear time-varying system whose robustness properties regarding the modeling errors are hard to be guaranteed. Nonetheless, as for the marine disturbances induced by the ocean waves, currents and winds, as well as the effects from the hydrodynamics, their interaction patterns with the AUVs are complicated and quite difficult to understand. In view of that, nonlinear robust control techniques, e.g., sliding mode control (SMC), have received much attention in various mechatronic control systems, for which a static switching-like feedback control law is used and the corresponding control gains are calculated to ensure that all types of disturbances, so long as within a given bound, can be handled[120–122].

Based on this paradigm, there is a variety of literature employing SMC schemes to study the robust tracking control problem of AUVs subject to both unknown disturbances and modeling uncertainties[123–126]. In particular, considering the potential time delays between surface ships and vehicles, which happens quite often in practical situations, the authors proposed a discrete-time quasi-SMC method for AUVs depth control to guarantee the stability and robustness even in the presence of large sampling intervals, and concurrently, the chattering was addressed using the so-called equivalent control region[127]. Besides the robustness, in order to meet a fast converging requirement near the equilibrium point, terminal sliding mode control (TSMC) techniques are used by researchers to achieve the finite time control[128–130]. Due to the possibility of singularity appearing in TSMC schemes, some non-singular TSMC approaches were investigated to avoid this issue[131–133]. While SMC based controllers exhibit a stunning robust performance in handling unknown environmental disturbances as well as inherent modeling uncertainties, a major drawback is that the chattering issue occurring in control activities should be carefully addressed, as it may inevitably deteriorate the performance in practical cases. Towards this end, higher-order SMC techniques were proposed to attenuate the high-frequency chattering to make SMC schemes more practical, and such methods were also applied to the control problems of AUVs tracking and formation[134–138]. To completely eliminate the chattering while obtaining good robustness, the authors developed a distributed neuro-dynamics-based sliding mode controller for the consensus formation tracking control of a group of AUVs[139]. In addition to the static robust control schemes that are considered more conservative, there are numerous disturbance observer-based controllers used for AUVs motion and formation control, which behave more actively in addressing the disturbances and hydrodynamic coefficients[140–145]. As well, observer-based schemes can also be used as an effective tool to tackle the output feedback control where the velocity sensing is unavailable, which is fairly beneficial in terms of reducing cost and meanwhile improving the performance of AUVs formation[146–149]. Furthermore, observer or estimator based techniques are also of critical importance and act as useful tools in designing systems of diagnosis and accommodation for sensor errors and faults. It is well known that failure to detect and isolate the errors and faults may lead to inaccurate control performance and even loss of the AUVs. To overcome it, the authors[150,151] employed certain observers and filters on the basis of vehicles' models to identify the errors in sensors and provide an estimate correspondingly, and thus a high-quality motion control objective can still be maintained.

Except for the handling of unknown disturbances and hydrodynamic uncertainties, avoiding obstacles and inter-vehicle collisions is another realistic aspect in synthesis of formation systems due to the poor knowledge of the obstacle distribution. To prevent unmanned aerial vehicles (UAVs) formation from any collisions, a collision avoidance mechanism was incorporated into the UAVs formation control strategy. In this approach, an additional velocity term is involved based on the mechanical impedance principle to avoid potential collisions, once the obstacles detected are within a certain range[152]. A new dual-mode strategy is designed to achieve cooperative UAV formation flying. In an obstacle-free environment, safe mode is activated to achieve global optimization. When faced with obstacles, danger mode enables a modified Grossberg neural network to plan an obstacle-free route, and a model predictive controller is also developed to achieve the route planned[153]. An obstacle avoidance strategy was proposed for UAV formation control design based on the artificial potential field (APF). An attractive potential field is designed for a leader to track the moving target, and the rest of the AUVs aims to follow the leader using the attractive potential force, while repulsive potential forces are also defined for UAVs to avoid obstacles[154]. Employing the same idea of APF, the authors proposed an obstacle-free formation controller for multi-agent systems based on virtual structure. To achieve the path planned by APF, a backstepping controller was developed based on the neural network and finite-time control technique[155]. Besides the APF-based obstacle avoiding strategies, as aforementioned, MPC-type controllers are capable of handling constraints effectively, which can be utilized to design collision-free formation controllers. This can be achieved by either extending the objective function or adding extra avoidance constraints into the receding horizon optimization procedure[156–159]. Other available approaches, such as ant colony algorithms[160,161], particle swarm optimization[162], machine learning-based algorithms[163], etc., were also reported to optimize an obstacle-free path, yet such intelligent optimization-based algorithms quite often necessitate a great computational effort and take a relatively long time, which greatly restricts their applications in AUVs formation where computation resources are limited and rapid response is needed to handle the variable surroundings.

4.3. Communication constraints

Different from the multiple land robots, surface vehicles and unmanned aerial vehicles, the signals of the global position system (GPS) or base stations cannot be received by AUVs in underwater conditions, and therefore the localization and communication in AUVs fleet may become an unavoidable issue. It has been turned out that the traditional acoustic technologies still serve as the most efficient way to provide the wireless connecting services[27], in which case the communication capability, thereby, has major impact on the performance of AUVs formation. The effects of the communication constraints mainly result from the following several aspects.

- Propagation delay: The speed of acoustic waves is nearly 1.5 kilometers per second, which is far slower than the speed of electromagnetic waves in air, and thus the effects of propagation delays cannot be neglected. Moreover, since the speed of the acoustic propagation relies highly on environmental factors (e.g., pressure, temperature, salinity, disturbances), the calculation for propagation delays may be rather complicated and often time-varying.
- Path loss: As the acoustic waves propagate, their energy spreads and attenuates in the medium. This process is called path loss, especially the higher the frequency, the easier the path loss. More path loss means a shorter communication range.
- Limited bandwidth: For a specific transition channel, its bandwidth is always limited and related to the range of communication. Therefore, it is necessary to allocate the interactive data reasonably (e.g., sensor

data, control data, localization data) in order to achieve an effective formation control.

- Multipath: During propagation, the acoustic signals could be reflected possibly by the sea surface, seabed and obstacles, which causes the multipath. Signals in multipath will result in distortion, consequently reducing the measurement or transmission accuracy.
- Doppler effect: Since the AUVs formation is always in motion, the frequency of the wave being transmitted by a moving base may be varied on its receiving side, which is called the Doppler effect.

There are a number of research efforts made to overcome the above communication constraints so that a better formation performance can be achieved. By assuming that the delays of propagation are bounded and the bounds on delays are less than the sampling period of AUVs, it was shown[164] that the leader-following based formation system can tolerate the delays and still achieve the formation stabilization, although it takes a longer time to stabilize than the case without delays. To provide a lower bound on control performance of an inspection ROV with sensor time delays, the authors employed an input-output controllability analysis to show that at which amount of delays the ROV system can tolerate irrespective of the forms of designed controllers, while the results are obtained based on an approximated linear model of the ROV[165]. As well, the researchers demonstrated by experiments that there exists a dominant time delay in the underwater acoustic positioning system powered by the short baseline (SBL) with four transducers, and that the traditional Smith predictor failed to estimate due to the time-varying properties. To handle it, an online identification was proposed in their work to estimate the variation of the delay, thus minimizing its impacts as much as possible[166]. To be able to account for the package dropouts, the authors[167] treated it as an extra delay out of the total delays and a compensating law was designed in the H_∞ controller to ensure a robust formation performance against delays. To characterize the delays more precisely, researchers[168] represent the delays as a differentiable function and suppose that its time derivative is less than one, under which a leader-following controller is designed to reach the formation requirements. To overcome the bandwidth limitation, an observer-based formation controller is quite often used to reduce the amount of information exchange, and furthermore, a fault function is introduced to describe the effect of the multipath in communication[169]. Nonetheless, as indicated[27], due to the fact that the information will be compressed before transmission, reducing control or sensor data do not contribute a lot to the relaxation of the bandwidth limitation. The authors provided a leader-following algorithm to optimize the formation configuration in terms of coverage efficacy and communication power consumption utilizing a calculation model for the path loss[170]. To reduce the Doppler effect, a Doppler effect compensation system is designed using an efficient multi-rate sampling technique[171]. Similarly, using diffident resampling strategies, reduction of the Doppler effect for the moving platform can be achieved[172,173]. Due to the unpredictable ambient disturbances and long communication distance, it is possible for the AUVs fleet to encounter a period of communication disconnection, in which case dynamic network topologies can be used to describe it. To achieve a dynamic topology, the authors predefine a set of topologies and put a random mechanism on it, and the objective is to design a formation controller such that the formation system can be stabilized under a jumped network topology[174,175]. Instead of random switching, a distance-based dynamic topology is defined among the group[176], in which merely the vehicles within the communication range can create the connection.

5. SUMMARY AND FUTURE WORK

We first provided several most commonly used coordinating structures and approaches to solve the AUVs formation control problem, that is, leader-following structure, virtual structure, behave-based approach, artificial potential field approach, and other approaches. It is noted that all of these mentioned approaches adopt a decentralized control architecture, i.e., each vehicle makes its own decisions based on the information received. In leader-following structure, there are one or several agents defined as leaders in advance to guide the whole formation system to meet the control requirements. Due to the advantages (e.g., easy implementation and analysis, and good flexibility), such a method has attracted much attention in most of the AUVs formation syntheses. A major deficiency is that the entire formation performance relies strongly on the leaders' behavior, thus often resulting in poor robustness. Although a virtual leader takes the place of the physical leaders, it still needs an assumption that each vehicle in the group is able to access the information of the leaders, which is obviously not realistic in real applications. Similarly, virtual structure approach seeks to convert the coupled coordination problem into the single vehicle tracking problem. In such a way, the analysis of the behavior of the overall formation system becomes trivial, since the stability and robustness of the overall system are simply ensured by the properties of single tracking systems. While straightforward and simple to realize, formation scaling is not that flexible compared to the leader-following approach, as the virtual reference points are predefined in accordance with the specified formation shape and cannot be changed during the formation process. In behavior-based approach, an apparent difference from above-mentioned methods is that mutual communication between neighbors is introduced, whereby it is possible for the agents to fulfill the formation demands using only the local information rather than the leaders' information, which seems to be more beneficial. Another benefit is that multi-goal can be achieved in this framework, e.g., formation keeping, target seeking, obstacle avoidance, etc. However, the major restriction of this method is that it is hard to analyze the behavior of the overall formation systems, especially in the case that the number of agents becomes large and the goals of the agents are complex, and thus cannot claim any theoretical guarantees to support its practical applications. Likewise, artificial potential field approach can be used to achieve the multi-objectives by means of the local interactions based on the so-called artificial potential field function. The analysis of the evolution of resulting systems is not easy as well due to the fact that the introduced potential functions are most likely to be nonlinear. Recently, the consensus-based approach has received enough attention, since it is able to provide a good trade-off between theoretical analysis and coordination performance. While the studies regarding consensus in the context of general muli-agent systems are extensive, because of the difficulties and special characteristics of the AUVs formation systems as mentioned above in Section 4, the research work adopting a consensus-based formation design is very limited.

Next, we categorized the several technical challenges and practical considerations in AUVs formation, that is, nonlinear uncertain dynamics of AUVs, complex underwater conditions, unknown disturbances and faults, and communication constraints. It is quite necessary to address them suitably and efficiently in order to obtain a better formation performance. Based on that, we reviewed in-depth the recent advances and developments in handling these pressing challenges. While, as observed above, there are an increasing number of research results being made to partly tackle some of these issues, due to the interdisciplinary nature of AUVs formation control systems, it is still far from mature and needs further research efforts. Based on the brief literature survey, some promising research directions are pointed out as follows.

- Due to the fact that the dynamics of AUVs are inherently nonlinear and uncertain subject to the underactuation and numerous constraints, high-quality motion control continues to be challenging. While there are some good frameworks that have been proven to be able to address these issues concurrently by combining the nonlinear control techniques (e.g., feedback linearization and backstepping design procedure) with MPC strategy[111–113], the performance of the resulting systems is dependent of the proposed auxiliary controllers, which may somehow tighten the region of attraction, and meanwhile such methods are usually computationally demanding. Thus, it is interesting to explore efficient nonlinear MPC schemes or other optimization-based approaches that are free from the auxiliary control laws simultaneously with fewer computation demands.
- Most of the existing solutions proposed are based on either the kinematic model or a reduced 2D dynamic model in the horizontal or vertical plane, which lack practicality, and therefore it is necessary to propose methods suitable for the general 3D case with more dynamic maneuvering tasks. Besides the stability, the systems' robustness properties against disturbances, noise and faults should be further established in order to synthesize more practical and robust controllers, but it seems that many existing results ignore the analysis on this aspect.
- In order to simplify the stability and robustness analysis, a good many available results are obtained based

on the leader-following structure. As aforementioned, such a method, although easy to implement, is not realistic and short of cooperation as it is assumed that the leaders' information needs to be received. In view of that, the consensus-based formation tracking control deserves further investigation.

- It is observed that many advanced formation control protocols developed assume perfect communication. As indicated above, addressing communication constraints (e.g., time-varying delays) is one of the most important points, as it is ubiquitous to encounter bad communication channels due to underwater conditions. Therefore, we believe that incorporating delay estimation and compensation techniques into formation control or designing delay-tolerant formation systems is of great significance in practice.
- While there are some primary proposals that provide several delay compensating strategies[165–168], most of them may be lack practicality due to the employment of an unrealistic delay model. Thus, more practical delay models are required, and then can be used to compensate for the impacts of the propagation delays. As suggested[27], most of the communication constraints can be ultimately grouped into the effects of delays, while the delays usually can be much more complicated. Thus, developing an effective estimation strategy for delays contributes to better formation control performance.
- In addition to the delays, due to the unpredictable underwater situations, it is possible to encounter a communication disconnection with neighboring agents, in which case the traditional fixed topology-based formation coordination strategy may fail to work. For this reason, developments of variable topology-based formation control protocols are of more practicality and robustness. While there exist some potential techniques suitable for handling this issue, as reported in *Tomera*'s work[177]where hybrid switching control theory was used to attempt to construct safety controller for a training ship operating in many modes, we believe more research efforts are still needed and relevant on this topic to derive a realistic switching mechanism for formation applications with consideration of characteristics of AUVs and communication.

In summary, because of the interdisciplinary feature of the AUVs formation applications, including the fields of mechanical, electrical, control and communication, many challenges and practical issues, as mentioned above, have not been well resolved and studied. In order to synthesize a practical and robust formation control system, we believe that it is imperative to take into consideration a suitable formation coordination structure, a realistic dynamic model of AUVs, disturbances, fault-tolerance and communication constraints.

6. CONCLUSION

This paper reviews the current advances and developments in the area of AUVs formation control systems, especially from the control point of view. We start with presenting the preliminaries on graph theory and AUVs mathematical models, both of which are essential to the analysis and synthesis of AUVs formation systems. Based on that, the formation control problem is stated. Then, several commonly used formation control protocols are listed, and the pros and cons of each method are summarized. After that, the technical challenges and practical issues confronted in AUVs formation control design are identified, and the existing available results to overcome these challenges are comprehensively surveyed, whereby we believe that the field is still at the early stage due to an apparent gap between theoretical progress and real-world applications. Finally, we summarize the paper and point out some prospective research directions worth further investigation.

DECLARATIONS

Authors' contributions

Made substantial contributions to the research and investigation process, reviewed and summarized the literature, wrote and edited the original draft: Yan T, Xu Z

Performed oversight and leadership responsibility for the research activity planning and execution as well as developed ideas and provided critical review, commentary and revision: Yang SX, Gadsden SA

Availability of data and materials

Not applicable.

Financial support and sponsorship

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Copyright

REFERENCES

1. Goheen KR, Jefferys ER. Multivariable self-tuning autopilots for autonomous and remotely operated underwater vehicles. *IEEE J Oceanic Eng* 1990;15:144–51. DOI
2. García-Valdovinos LG, Salgado-Jiménez T, Bandala-Sánchez M, Nava-Balanzar L, Hernández-Alvarado R, Cruz-ledesma JA. Modelling, Design and robust control of a remotely operated underwater vehicle. *Int J Adv Robot Syst* 2014;11:1. DOI
3. Reisenbichler KR, Chaffey MR, Cazenave F, et al. Automating MBARI's midwater time-series video surveys: The transition from ROV to AUV. In: OCEANS 2016 MTS/IEEE Monterey; 2016. pp. 1–9. DOI
4. Petillot YR, Antonelli G, Casalino G, Ferreira F. underwater robots: from remotely operated vehicles to intervention-autonomous underwater vehicles. *IEEE Robot Automat Mag* 2019;26:94–101. DOI
5. Wynn RB, Huvenne VAI, Le Bas TP, et al. Autonomous underwater vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. *Marine Geology* 2014;352:451–68. DOI
6. Shi Y, Shen C, Fang H, Li H. Advanced control in marine mechatronic systems: a survey. *IEEE/ASME Trans Mechatron* 2017;22:1121-31. DOI
7. Li J, Xu Z, Zhu D, et al. Bio-inspired intelligence with applications to robotics: a survey. *Intell Robot* 2021;1:58–83. DOI
8. Fossen TI. Guidance and control of ocean vehicles. University of Trondheim, Norway, Printed by John Wiley & Sons, Chichester, England, ISBN: 0 471 94113 1, Doctors Thesis 1999. DOI
9. Bogue R. Underwater robots: a review of technologies and applications. *Indus Robot* 2015;42:186-91. DOI
10. Gafurov SA, Klochkov EV. Autonomous unmanned underwater vehicles development tendencies. *Procedia Engineering* 2015;106:141–48. DOI
11. Oh KK, Park MC, Ahn HS. A survey of multi-agent formation control. *Automatica* 2015;53:424–40. DOI
12. Alam K, Ray T, Anavatti SG. A brief taxonomy of autonomous underwater vehicle design literature. *Ocean Engineering* 2014;88:627-30. DOI
13. Sousa J, Cruz N, Matos A, Pereira FL. Multiple AUVs for coastal oceanography. In: Oceans' 97. MTS/IEEE Conference Proceedings. vol. 1. IEEE; 1997. pp. 409–14. DOI
14. Singh H, Catipovic J, Eastwood R, et al. An integrated approach to multiple AUV communications, navigation and docking. In: OCEANS 96 MTS/IEEE Conference Proceedings. The Coastal Ocean-Prospects for the 21st Century. vol. 1. IEEE; 1996. pp. 59–64. DOI
15. Sotzing CC, Evans J, Lane DM. A multi-agent architecture to increase coordination efficiency in multi-auv operations. In: OCEANS 2007-Europe. IEEE; 2007. pp. 1–6. DOI
16. Yu W, Chen G, Cao M. Distributed leader–follower flocking control for multi-agent dynamical systems with time-varying velocities. *Syst Contr Letters* 2010;59:543–52. DOI
17. Yamaguchi H. A cooperative hunting behavior by mobile-robot troops. *Int J Robot Res* 1999;18:931–40. DOI
18. Vidal R, Shakernia O, Kim HJ, Shim DH, Sastry S. Probabilistic pursuit-evasion games: theory, implementation, and experimental evaluation. *IEEE Trans Robot Automat* 2002;18:662-9. DOI
19. Chung TH, Hollinger GA, Isler V. Search and pursuit-evasion in mobile robotics. *Auton Robot* 2011;31:299-316. DOI
20. Hespanha JP, Kim HJ, Sastry S. Multiple-agent probabilistic pursuit-evasion games. In: Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No. 99CH36304). vol. 3. IEEE; 1999. pp. 2432–37. DOI
21. Guler S, Fidan B, Gazi V. Adaptive swarm coordination and formation control. In: Tan Y, editor. Handbook of Research on Design, Control, and Modeling of Swarm Robotics. IGI Global; 2016. pp. 175-206. DOI

22. Yan J, Yang X, Luo X, Chen C. Energy-efficient data collection over AUV-assisted underwater acoustic sensor network. *IEEE Syst J* 2018;12:3519-30. DOI
23. Huang M, Zhang K, Zeng Z, Wang T, Liu Y. An AUV-assisted data gathering scheme based on clustering and matrix completion for smart ocean. *IEEE Internet Things J* 2020;7:9904-18. DOI
24. Duan R, Du J, Ren J, et al. VoI based information collection for AUV assisted underwater acoustic sensor networks. In: ICC 2020-2020 IEEE International Conference on Communications (ICC). IEEE; 2020. pp. 1–6. DOI
25. Tan HP, Diamant R, Seah WK, Waldmeyer M. A survey of techniques and challenges in underwater localization. *Ocean Engineering* 2011;38:1663-76. DOI
26. Kinsey JC, Eustice RM, Whitcomb LL. A survey of underwater vehicle navigation: Recent advances and new challenges. In: IFAC conference of manoeuvering and control of marine craft. vol. 88. Lisbon; 2006. pp. 1–12. DOI
27. Yang Y, Xiao Y, Li T. A survey of autonomous underwater vehicle formation: Performance, formation control, and communication capability. *IEEE Commun Surv Tutorials* 2021;23:815-41. DOI
28. Fossen TI. Handbook of marine craft hydrodynamics and motion control. Chichester: John Wiley & Sons, Ltd; 2011. pp. 343-415. DOI
29. Das B, Subudhi B, Pati BB. Cooperative formation control of autonomous underwater vehicles: an overview. *Int J Autom Comput* 2016;13:199-225. DOI
30. Wei X, Wang X, Bai X, Bai S, Liu J. Autonomous underwater vehicles localisation in mobile underwater networks. *IJSNET* 2017;23:61. DOI
31. Chen YQ, Wang Z. Formation control: a review and a new consideration. In: 2005 IEEE/RSJ International conference on intelligent robots and systems. IEEE; 2005. pp. 3181–86. DOI
32. Issa B, Rashid AT. A survey of multi-mobile robot formation control. *IJCA* 2019;181:12-6. DOI
33. Zhang Y, Mehrjerdi H. A survey on multiple unmanned vehicles formation control and coordination: Normal and fault situations. In: 2013 International conference on unmanned aircraft systems (ICUAS). IEEE; 2013. pp. 1087–96. DOI
34. Do HT, Hua HT, Nguyen MT, et al. Formation control algorithms for multiple-uavs: a comprehensive survey. *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems* 2021;8:e3–e3. DOI
35. Ziquan Y, Zhang Y, Jiang B, Jun F, Ying J. A review on fault-tolerant cooperative control of multiple unmanned aerial vehicles. *Chinese J Aeronaut* 2022;35:1–18. DOI
36. Cai G, Dias J, Seneviratne L. A survey of small-scale unmanned aerial vehicles: recent advances and future development trends. *Un Sys* 2014;02:175-99. DOI
37. Dong X, Yu B, Shi Z, Zhong Y. Time-varying formation control for unmanned aerial vehicles: Theories and applications. *IEEE Trans Contr Syst Technol* 2015;23:340-8. DOI
38. Scharf DP, Hadaegh FY, Ploen SR. A survey of spacecraft formation flying guidance and control. part ii: control. In: Proceedings of the 2004 American control conference. vol. 4. Ieee; 2004. pp. 2976–85. DOI
39. Liu GP, Zhang S. A survey on formation control of small satellites. *Proc IEEE* 2018;106:440-57. DOI
40. Yuh J. Design and control of autonomous underwater robots: a survey. Autonomous Robots 2000;8:7–24. DOI
41. Li X, Zhu D, Qian Y. A survey on formation control algorithms for multi-AUV system. *Un Sys* 2014;02:351-9. DOI
42. Hadi B, Khosravi A, Sarhadi P. A review of the path planning and formation control for multiple autonomous underwater vehicles. *J Intell Robot Syst* 2021;101. DOI
43. Wang X, Zerr B, Thomas H, Clement B, Xie Z. Pattern formation of multi-AUV systems with the optical sensor based on displacement-based formation control. *Int J Syst Sci* 2020;51:348-67. DOI
44. Edwards D, Bean T, Odell D, Anderson M. A leader-follower algorithm for multiple AUV formations. In: 2004 IEEE/OES Autonomous Underwater Vehicles (IEEE Cat. No. 04CH37578). IEEE; 2004. pp. 40–46. DOI
45. Ren W, Sorensen N. Distributed coordination architecture for multi-robot formation control. *Robot Auton Syst* 2008;56:324–33. DOI
46. Cui R, Ge SS, How BVE, Choo YS. Leader–follower formation control of underactuated autonomous underwater vehicles. *Ocean Engineering* 2010;37:1491–502. DOI
47. Zheng J, Huang Y, Xiao Y. The effect of leaders on the consistency of group behaviour. *IJSNET* 2012;11:126–35. DOI
48. Cao X, Guo L. A leader–follower formation control approach for target hunting by multiple autonomous underwater vehicle in three-dimensional underwater environments. *Int J Adv Robot Syst* 2019;16:1729881419870664. DOI
49. Shi H, Wang L, Chu T. Virtual leader approach to coordinated control of multiple mobile agents with asymmetric interactions. *Physica D: Nonlinear Phenomena* 2006;213:51–65. DOI
50. Droge G. Distributed virtual leader moving formation control using behavior-based MPC. In: 2015 American Control Conference (ACC). IEEE; 2015. pp. 2323–28. DOI
51. Zheping Y, Yibo L, Jiajia Z, Gengshi Z. Moving target following control of multi-auvs formation based on rigid virtual leader-follower under ocean current. In: 2015 34th Chinese control conference (CCC). IEEE; 2015. pp. 5901–6. DOI
52. Li J, Du X. Underactuated multi-AUV robust formation control based on virtual leader. In: 2018 IEEE International Conference on Mechatronics and Automation (ICMA). IEEE; 2018. pp. 1568–73. DOI
53. Tan KH, Lewis MA. Virtual structures for high-precision cooperative mobile robotic control. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS'96. vol. 1. IEEE; 1996. pp. 132–39. DOI
54. Lewis MA, Tan KH. High precision formation control of mobile robots using virtual structures. *Auton Robot* 1997;4:387–403. DOI
55. Ren W, Beard RW. Decentralized scheme for spacecraft formation flying via the virtual structure approach. *Journal of Guidance, Control, and Dynamics* 2004;27:73–82. DOI

56. Yuan J, Tang GY. Formation control for mobile multiple robots based on hierarchical virtual structures. In: IEEE ICCA 2010. IEEE; 2010. pp. 393–98. DOI
57. Zhang Lc, Wang J, Wang T, Liu M, Gao J. Optimal formation of multiple AUVs cooperative localization based on virtual structure. In: OCEANS 2016 MTS/IEEE Monterey. IEEE; 2016. pp. 1–6. DOI
58. Zhen Q, Wan L, Li Y, Jiang D. Formation control of a multi-AUVs system based on virtual structure and artificial potential field on SE (3). *Ocean Engineering* 2022;253:111148. DOI
59. Yuan C, Licht S, He H. Formation learning control of multiple autonomous underwater vehicles with heterogeneous nonlinear uncertain dynamics. *IEEE Trans Cybern* 2018;48:2920-34. DOI
60. Balch T, Arkin RC. Behavior-based formation control for multirobot teams. *IEEE Trans Robot Automat* 1998;14:926–39. DOI
61. Monteiro S, Bicho E. A dynamical systems approach to behavior-based formation control. In: Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292). vol. 3. IEEE; 2002. pp. 2606–11. DOI
62. Xiaomin M, Yang D, Xing L, Sentang W. Behavior-based formation control of multi-missiles. In: 2009 Chinese Control and Decision Conference. IEEE; 2009. pp. 5019–23. DOI
63. Xu D, Zhang X, Zhu Z, Chen C, Yang P. Behavior-based formation control of swarm robots. *Mathematical Problems in Engineering* 2014;2014:1-13. DOI
64. Hacene N, Mendil B. Behavior-based autonomous navigation and formation control of mobile robots in unknown cluttered dynamic environments with dynamic target tracking. *Int J Autom Comput* 2021;18:766-86. DOI
65. Khatib O. Real-time obstacle avoidance for manipulators and mobile robots. In: Cox IJ, Wilfong GT, editors. Autonomous Robot Vehicles. New York: Springer; 1990. pp. 396-404. DOI
66. Gazi V. Swarm aggregations using artificial potentials and sliding-mode control. *IEEE Trans Robot* 2005;21:1208-14. DOI
67. Fiorelli E, Leonard NE, Bhatta P, Paley DA, Bachmayer R, et al. Multi-AUV control and adaptive sampling in Monterey Bay. *IEEE J Oceanic Eng* 2006;31:935-48. DOI
68. Barnes L, Fields M, Valavanis K. Unmanned ground vehicle swarm formation control using potential fields. In: 2007 Mediterranean Conference on Control & Automation. IEEE; 2007. pp. 1–8. DOI
69. Pereira AR, Hsu L. Adaptive formation control using artificial potentials for Euler-Lagrange agents. *IFAC Proceedings Volumes* 2008;41:10788–93. DOI
70. Sabattini L, Secchi C, Fantuzzi C. Arbitrarily shaped formations of mobile robots: artificial potential fields and coordinate transformation. *Auton Robot* 2011;30:385-97. DOI
71. Nair RR, Behera L, Kumar V, Jamshidi M. Multisatellite formation control for remote sensing applications using artificial potential field and adaptive fuzzy sliding mode control. *IEEE Syst* J2014;9:508–18. DOI
72. Ying Z, Xu L. Leader-follower formation control and obstacle avoidance of multi-robot based on artificial potential field. In: The 27th Chinese Control and Decision Conference (2015 CCDC). IEEE; 2015. pp. 4355–60. DOI
73. Ihle IA, Skjetne R, Fossen TI. Nonlinear formation control of marine craft with experimental results. In: 2004 43rd IEEE Conference on Decision and Control (CDC)(IEEE Cat. No. 04CH37601). vol. 1. IEEE; 2004. pp. 680–85. DOI
74. Cui R, Xu D, Yan W. Formation control of autonomous underwater vehicles under fixed topology. In: 2007 IEEE International Conference on Control and Automation. IEEE; 2007. pp. 2913–18. DOI
75. Yu W, Wen G, Chen G, Cao J. Distributed cooperative control of multi-agent systems. John Wiley & Sons; 2017.
76. Fink A, Kosecoff J, Chassin M, Brook RH. Consensus methods: characteristics and guidelines for use. *Am J Public Health* 1984;74:979-83. DOI
77. Ren W, Beard RW, Atkins EM. A survey of consensus problems in multi-agent coordination. In: Proceedings of the 2005, American Control Conference, 2005. IEEE; 2005. pp. 1859–64. DOI
78. Ren W, Beard RW, McLain TW. Coordination variables and consensus building in multiple vehicle systems. In: Kumar V, Leonard N, Morse AS, editors. Cooperative Control. Berlin: Springer Berlin Heidelberg; 2005. pp. 171-88. DOI
79. Olfati-Saber R, Fax JA, Murray RM. Consensus and cooperation in networked multi-agent systems. *Proc IEEE* 2007;95:215-33. DOI
80. Anderson BD, Yu C, Fidan B, Hendrickx JM. Rigid graph control architectures for autonomous formations. *IEEE Control Syst* 2008;28:48-63. DOI
81. Mesbahi M, Egerstedt M. Graph theoretic methods in multiagent networks. In: Graph Theoretic Methods in Multiagent Networks. Princeton University Press; 2010. DOI
82. Ren W. Consensus based formation control strategies for multi-vehicle systems. In: 2006 American Control Conference. IEEE; 2006. pp. 6–pp. DOI
83. Porfiri M, Roberson DG, Stilwell DJ. Tracking and formation control of multiple autonomous agents: a two-level consensus approach. *Automatica* 2007;43:1318–28. DOI
84. Luo X, Han N, Guan X. Leader-following consensus protocols for formation control of multi-agent network. *J Syst Eng Electron* 2011;22:991-7. DOI
85. Dong R, Geng Z. Consensus based formation control laws for systems on Lie groups. *Syst Contr Letters* 2013;62:104–11. DOI
86. Dong R, Geng Z. Consensus for formation control of multi-agent systems. *Int J Robust Nonlinear Control* 2015;25:2481-501. DOI
87. Falconi R, Sabattini L, Secchi C, Fantuzzi C, Melchiorri C. Edge-weighted consensus-based formation control strategy with collision avoidance. *Robotica* 2015;33:332–47. DOI
88. Listmann KD, Masalawala MV, Adamy J. Consensus for formation control of nonholonomic mobile robots. In: 2009 IEEE international conference on robotics and automation. IEEE; 2009. pp. 3886–91. DOI

89. Wang W, Huang J, Wen C, Fan H. Distributed adaptive control for consensus tracking with application to formation control of nonholonomic mobile robots. *Automatica* 2014;50:1254–63. DOI
90. Peng Z, Wen G, Rahmani A, Yu Y. Distributed consensus-based formation control for multiple nonholonomic mobile robots with a specified reference trajectory. *Int J Syst Sci* 2015;46:1447–57. DOI
91. Peng Z, Wen G, Yang S, Rahmani A. Distributed consensus-based formation control for nonholonomic wheeled mobile robots using adaptive neural network. *Nonlinear Dynamics* 2016;86:605–22. DOI
92. Cheng Y, Jia R, Du H, Wen G, Zhu W. Robust finite-time consensus formation control for multiple nonholonomic wheeled mobile robots via output feedback. *Int J Robust Nonlinear Control* 2018;28:2082-96. DOI
93. Kuriki Y, Namerikawa T. Consensus-based cooperative formation control with collision avoidance for a multi-UAV system. In: 2014 American Control Conference. IEee; 2014. pp. 2077–82. DOI
94. Kuriki Y, Namerikawa T. Formation control with collision avoidance for a multi-UAV system using decentralized MPC and consensus-based control. *SICE Journal of Control, Measurement, and System Integration* 2015;8:285–94. DOI
95. Mu B, Li H, Ding J, Shi Y. Consensus in second-order multiple flying vehicles with random delays governed by a Markov chain. *Journal of the Franklin Institute* 2015;352:3628–44. DOI
96. Du H, Zhu W, Wen G, Duan Z, Lü J. Distributed formation control of multiple quadrotor aircraft based on nonsmooth consensus algorithms. *IEEE Trans Cybern* 2019;49:342-53. DOI
97. Kuo CW, Tsai CC, Lee CT. Intelligent leader-following consensus formation control using recurrent neural networks for small-size unmanned helicopters. *IEEE Trans Syst Man Cybern, Syst* 2021;51:1288-301. DOI
98. Wu Y, Gou J, Hu X, Huang Y. A new consensus theory-based method for formation control and obstacle avoidance of UAVs. *Aerospace Science and Technology* 2020;107:106332. DOI
99. Ren W. Distributed attitude consensus among multiple networked spacecraft. In: 2006 American control conference. IEEE; 2006. pp. 6–pp. DOI
100. Ren W. Distributed attitude alignment in spacecraft formation flying. *Int J Adapt Control Signal Process* 2007;21:95-113. DOI
101. Guiming L, Liangdong L. Coordinated multiple spacecraft attitude control with communication time delays and uncertainties. Chinese J Aeronaut 2012;25:698–708. DOI
102. Nazari M, Butcher EA, Yucelen T, Sanyal AK. Decentralized consensus control of a rigid-body spacecraft formation with communication delay. *Journal of Guidance, Control, and Dynamics* 2016;39:838-51. DOI
103. Silvestre C, Pascoal A. Control of the INFANTE AUV using gain scheduled static output feedback. *Control Engineering Practice* 2004;12:1501–9. DOI
104. Kaminer I, Pascoal AM, Khargonekar PP, Coleman EE. A velocity algorithm for the implementation of gain-scheduled controllers. *Automatica* 1995;31:1185–91. DOI
105. Mohamed SA, Osman AA, Attia SA, Maged SA. Dynamic model and control of an autonomous underwater vehicle. In: 2020 International Conference on Innovative Trends in Communication and Computer Engineering (ITCE). IEEE; 2020. pp. 182–90. DOI
106. Nag A, Patel SS, Kishore K, Akbar S. A robust H-infinity based depth control of an autonomous underwater vehicle. In: 2013 International Conference on Advanced Electronic Systems (ICAES). IEEE; 2013. pp. 68–73. DOI
107. Zhang Y, Liu X, Luo M, Yang C. MPC-based 3-D trajectory tracking for an autonomous underwater vehicle with constraints in complex ocean environments. *Ocean Engineering* 2019;189:106309. DOI
108. Naeem W, Sutton R, Ahmad S. LQG/LTR control of an autonomous underwater vehicle using a hybrid guidance law. *IFAC Proceedings Volumes* 2003;36:31–36. DOI
109. Long C, Qin X, Bian Y, Hu M. Trajectory tracking control of ROVs considering external disturbances and measurement noises using ESKF-based MPC. *Ocean Engineering* 2021;241:109991. DOI
110. Chellabi A, Nahon M. Feedback linearization control of undersea vehicles. In: Proceedings of OCEANS '93; 1993. pp. I410–ol.1. DOI
111. Shen C, Shi Y, Buckham B. Trajectory tracking control of an autonomous underwater vehicle using Lyapunov-based model predictive control. *IEEE Trans Ind Electron* 2018;65:5796-805. DOI
112. Shen C, Shi Y, Buckham B. Nonlinear model predictive control for trajectory tracking of an AUV: A distributed implementation. In: 2016 IEEE 55th Conference on Decision and Control (CDC). IEEE; 2016. pp. 5998–6003. DOI
113. Li H, Xie P, Yan W. Receding horizon formation tracking control of constrained underactuated autonomous underwater vehicles. *IEEE Trans Ind Electron* 2017;64:5004-13. DOI
114. Wei H, Shen C, Shi Y. Distributed Lyapunov-based model predictive formation tracking control for autonomous underwater vehicles subject to disturbances. *IEEE Trans Syst Man Cybern, Syst* 2019;51:5198–208. DOI
115. Khodayari MH, Balochian S. Modeling and control of autonomous underwater vehicle (AUV) in heading and depth attitude via self-adaptive fuzzy PID controller. *J Mar Sci Technol* 2015;20:559-78. DOI
116. Liang X, Qu X, Wan L, Ma Q. Three-dimensional path following of an underactuated AUV based on fuzzy backstepping sliding mode control. *Int J Fuzzy Systl* 2018;20:640-9. DOI
117. Nan D, Weng Y, Liu Y, Wang X. Accurate trajectory tracking control of unknown autonomous underwater vehicles: A data-driven predictive approach. In: 2021 IEEE 10th Data Driven Control and Learning Systems Conference (DDCLS). IEEE; 2021. pp. 1241–45. DOI
118. Wang D, He B, Shen Y, Li G, Chen G. A Modified ALOS Method of Path Tracking for AUVs with Reinforcement Learning Accelerated by Dynamic Data-Driven AUV Model. *J Intell Robot Syst* 2022;104:1–23. DOI
119. Shojaei K. Neural network formation control of underactuated autonomous underwater vehicles with saturating actuators. *Neurocom-*

puting 2016;194:372–84. DOI
120. Young KD, Utkin VI, Ozguner U. A control engineer's guide to sliding mode control. *IEEE Trans Contr Syst Technol* 1999;7:328–42. DOI
121. Edwards C, Spurgeon S. Sliding mode control: theory and applications. Crc Press; 1998. DOI
122. Perruquetti W, Barbot JP. Sliding mode control in engineering. vol. 11. Marcel Dekker New York; 2002. DOI
123. Yan Z, Wang M, Xu J. Robust adaptive sliding mode control of underactuated autonomous underwater vehicles with uncertain dynamics. Ocean Engineering 2019;173:802–9. DOI
124. Guo Y, Qin H, Xu B, Han Y, Fan QY, et al. Composite learning adaptive sliding mode control for AUV target tracking. *Neurocomputing* 2019;351:180–86. DOI
125. Huang B, Yang Q. Double-loop sliding mode controller with a novel switching term for the trajectory tracking of work-class ROVs. *Ocean Engineering* 2019;178:80–94. DOI
126. Yan Y, Yu S. Sliding mode tracking control of autonomous underwater vehicles with the effect of quantization. *Ocean Engineering* 2018;151:322–28. DOI
127. Lee PM, Hong SW, Lim YK, et al. Discrete-time quasi-sliding mode control of an autonomous underwater vehicle. *IEEE J Oceanic Eng*1999;24:388–95. DOI
128. Zhihong M, Yu XH. Terminal sliding mode control of MIMO linear systems. *IEEE Trans Circuits Syst I* 1997;44:1065-70. DOI
129. Wang Y, Gu L, Gao M, Zhu K. Multivariable output feedback adaptive terminal sliding mode control for underwater vehicles. *Asian J Contr* 2016;18:247–65. DOI
130. Elmokadem T, Zribi M, Youcef-Toumi K. Terminal sliding mode control for the trajectory tracking of underactuated Autonomous Underwater Vehicles. textitOcean Engineering 2017;129:613–25. DOI
131. Qiao L, Zhang W. Adaptive non-singular integral terminal sliding mode tracking control for autonomous underwater vehicles. textitIET Control Theory & Applications 2017;11:1293–306. DOI
132. Patre B, Londhe P, Waghmare L, Mohan S. Disturbance estimator based non-singular fast fuzzy terminal sliding mode control of an autonomous underwater vehicle. textitOcean Engineering 2018;159:372–87. DOI
133. Rangel MAG, Manzanilla A, Suarez AEZ, Muñoz F, Salazar S, et al. Adaptive non-singular terminal sliding mode control for an unmanned underwater vehicle: Real-time experiments. textitInt J Control Autom Syst 2020;18:615-28. DOI
134. Salgado-Jimenez T, Spiewak JM, Fraisse P, Jouvencel B. A robust control algorithm for AUV: based on a high order sliding mode. In: Oceans' 04 MTS/IEEE Techno-Ocean'04 (IEEE Cat. No. 04CH37600). vol. 1. IEEE; 2004. pp. 276–81. DOI
135. Li X, Zhu D. Formation control of a group of AUVs using adaptive high order sliding mode controller. In: OCEANS 2016-Shanghai. IEEE; 2016. pp. 1–6. DOI
136. Guerrero J, Antonio E, Manzanilla A, Torres J, Lozano R. Autonomous underwater vehicle robust path tracking: Auto-adjustable gain high order sliding mode controller. textitIFAC-PapersOnLine 2018;51:161–66. DOI
137. Wang J, Wang C, Wei Y, Zhang C. Sliding mode based neural adaptive formation control of underactuated AUVs with leader-follower strategy. textitApplied Ocean Research 2020;94:101971. DOI
138. Borlaug ILG, Pettersen KY, Gravdahl JT. Comparison of two second-order sliding mode control algorithms for an articulated intervention AUV: Theory and experimental results. textitOcean Engineering 2021;222:108480. DOI
139. Yan T, Xu Z, Yang SX. Consensus Formation Control for Multiple AUVSystems Using Distributed Bioinspired Sliding Mode Control. textitIEEE Trans Intell Veh 2022:1–1. DOI
140. Xu H, Zhang Gc, Cao J, Pang S, Sun Ys. Underactuated AUV nonlinear finite-time tracking control based on command filter and disturbance observer. textitSensors (Basel) 2019;19:4987. DOI
141. Guerrero J, Torres J, Creuze V, Chemori A. Adaptive disturbance observer for trajectory tracking control of underwater vehicles. textitOcean Engineering 2020;200:107080. DOI
142. Gao Z, Guo G. Fixed-time sliding mode formation control of AUVs based on a disturbance observer. textitIEEE/CAA J Autom Sinica 2020;7:539-45. DOI
143. Su B, Wang Hb, Wang Y. Dynamic event-triggered formation control for AUVs with fixed-time integral sliding mode disturbance observer. textitOcean Engineering 2021;240:109893. DOI
144. Wang H, Su B. Event-triggered formation control of AUVs with fixed-time RBF disturbance observer. textitApplied Ocean Research 2021;112:102638. DOI
145. Li J, Du J, Chang WJ. Robust time-varying formation control for underactuated autonomous underwater vehicles with disturbances under input saturation. textitOcean Engineering 2019;179:180–88. DOI
146. Gao Z, Guo G. Velocity free leader-follower formation control for autonomous underwater vehicles with line-of-sight range and angle constraints. textitInformation Sciences 2019;486:359–78. DOI
147. Wang J, Wang C, Wei Y, Zhang C. Observer-Based Neural Formation Control of Leader–Follower AUVs With Input Saturation. textitIEEE Syst J 2021;15:2553-61. DOI
148. Chen B, Hu J, Zhao Y, Ghosh BK. Finite-time velocity-free observer-based consensus tracking for heterogeneous uncertain AUVs via adaptive sliding mode control. textitOcean Engineering 2021;237:109565. DOI
149. Yan Z, Zhang C, Tian W, Cai S, Zhao L. Distributed observer-based formation trajectory tracking method of leader-following multi-AUV system. textitOcean Engineering 2022;260:112019. DOI
150. Filaretov V, Zhirabok A, Zuev A, Procenko A. The development of system of accommodation to faults of navigation sensors of underwater vehicles with resistance to disturbance. In: 2014 14th International Conference on Control, Automation and Systems (ICCAS 2014);

2014. pp. 1548–53. DOI
151. Xia Y, Xu K, Wang W, et al. Optimal robust trajectory tracking control of a X-rudder AUV with velocity sensor failures and uncertainties. textitOcean Engineering 2020;198:106949. DOI
152. Liu Z, Yu X, Yuan C, Zhang Y. Leader-follower formation control of unmanned aerial vehicles with fault tolerant and collision avoidance capabilities. In: 2015 international conference on unmanned aircraft systems (ICUAS). IEEE; 2015. pp. 1025–30. DOI
153. Wang X, Yadav V, Balakrishnan SN. Cooperative UAV Formation Flying With Obstacle/Collision Avoidance. textitIEEE Trans Contr Syst Technol 2007;15:672–79. [DOI: 10.1109/TCST.2007.899191] DOI
154. Chang K, Xia Y, Huang K. UAV formation control design with obstacle avoidance in dynamic three-dimensional environment. textitSpringerPlus 2016;5:1–16. DOI
155. Shou Y, Xu B, Lu H, Zhang A, Mei T. Finite-time formation control and obstacle avoidance of multi-agent system with application. textitIntl J Robust & Nonlinear 2022;32:2883-901. DOI
156. Lobo Pereira F, Borges de Sousa J, Gomes R, Calado P. A model predictive control approach to AUVs motion coordination. In: van Schuppen JH, Villa T, editors. Coordination Control of Distributed Systems. Cham: Springer International Publishing; 2015. pp. 9-18. DOI
157. Guo H, Shen C, Zhang H, Chen H, Jia R. Simultaneous trajectory planning and tracking using an MPC method for cyber-physical systems: A case study of obstacle avoidance for an intelligent vehicle. textitIEEE Trans Ind Inf 2018;14:4273-83. DOI
158. Wang X, Yao X, Zhang L. Path planning under constraints and path following control of autonomous underwater vehicle with dynamical uncertainties and wave disturbances. textitJ Intell Robot Syst 2020;99:891–908. DOI
159. Lindqvist B, Mansouri SS, Agha-mohammadi Aa, Nikolakopoulos G. Nonlinear MPC for collision avoidance and control of UAVs with dynamic obstacles. textitIEEE Robot Autom Lett 2020;5:6001–8. DOI
160. Zhang Gl, Jia Hm. Global path planning of AUV based on improved ant colony optimization algorithm. In: 2012 IEEE International Conference on Automation and Logistics. IEEE; 2012. pp. 606–10. DOI
161. Lin C, Wang H, Yuan J, Fu M. An online path planning method based on hybrid quantum ant colony optimization for AUV. textitInt J Robot Autom 2018;33:435–44. DOI
162. Phung MD, Quach CH, Dinh TH, Ha Q. Enhanced discrete particle swarm optimization path planning for UAV vision-based surface inspection. textitAutom Construction 2017;81:25–33. DOI
163. Wang D, Fan T, Han T, Pan J. A two-stage reinforcement learning approach for multi-UAV collision avoidance under imperfect sensing. textitIEEE Robot Autom Lett 2020;5:3098-105. DOI
164. Yan Z, Yang Z, Yue L, et al. Discrete-time coordinated control of leader-following multiple AUVs under switching topologies and communication delays. textitOcean Engineering 2019;172:361–72. DOI
165. Sørensen FF, von Benzon M, Liniger J, Pedersen S. A quantitative parametric study on output time delays for autonomous underwater cleaning operations. textitJMSE 2022;10:815. DOI
166. Pedersen S, Liniger J, Sørensen FF, Schmidt K, von Benzon M, et al. Stabilization of a ROV in three-dimensional space using an underwater acoustic positioning system. textitIFAC-PapersOnLine 2019;52:117–22. DOI
167. Millán P, Orihuela L, Jurado I, Rubio FR. Formation control of autonomous underwater vehicles subject to communication delays. textitIEEE Trans Contr Syst Technol 2013;22:770–77. DOI
168. Yan Z, Pan X, Yang Z, Yue L. Formation control of leader-following multi-UUVs with uncertain factors and time-varying delays. textitIEEE Access 2019;7:118792–805. DOI
169. Chen S, Ho DW. Consensus control for multiple AUVs under imperfect information caused by communication faults. textitInformation Sciences 2016;370-371:565-77. DOI
170. Burlutskiy N, Touahmi Y, Lee BH. Power efficient formation configuration for centralized leader–follower AUVs control. textitJ Mar Sci Technol 2012;17:315–29. DOI
171. Sharif BS, Neasham J, Hinton OR, Adams AE. A computationally efficient Doppler compensation system for underwater acoustic communications. textitIEEE J Oceanic Eng 2000;25:52–61. DOI
172. Li B, Zhou S, Stojanovic M, Freitag L, Willett P. Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts. textitIEEE J Oceanic Eng 2008;33:198–209. DOI
173. Yoshizawa S, Saito T, Mabuchi Y, Tsukui T, Sawada S. Parallel resampling of OFDM signals for fluctuating doppler shifts in underwater acoustic communication. textitJ Electr Compu Eng 2018;2018:1-11. DOI
174. Hu Z, Ma C, Zhang L, et al. Formation control of impulsive networked autonomous underwater vehicles under fixed and switching topologies. textitNeurocomputing 2015;147:291–98. DOI
175. Yan Z, Xu D, Chen T, Zhang W, Liu Y. Leader-follower formation control of UUVs with model uncertainties, current disturbances, and unstable communication. textitSensors 2018;18:662. DOI
176. Seuret A, de Wit CC, et al. Contraction control of a fleet circular formation of AUVs under limited communication range. In: Proceedings of the 2010 American Control Conference. IEEE; 2010. pp. 5991–96. DOI
177. Tomera M. Hybrid switching controller design for the maneuvering and transit of a training ship. textitInt J Appl Mathem Compu Sci 2017;27:63–77. DOI