# A Survey of Autonomous Underwater Vehicle Formation: Performance, Formation Control, and Communication Capability

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***Abstract*—Autonomous underwater vehicles (AUVs) are submersible underwater vehicles controlled by onboard computers. AUV formation is a cooperative control which focuses on controlling multiple AUVs to move in a group while executing tasks. In contrast to a single AUV, multi-AUV formation represents higher efficiency and better stability for many applications, such as oil and gas industries, hydrographic surveys, and military missions, etc. To achieve better formation, there are several key factors, including AUV performance, formation control, and communication capability. However, most studies in the field of AUV formation mainly focus on formation control methods. We observe that the research of communication capability and AUV performance of multiple AUV formation is still in an early stage. It is beneficial to researchers to present a comprehensive survey of the state of the art of AUV formation research and development. In this paper, we study AUV, formation control, and underwater acoustic communication capability in detail. We propose a classification framework with three dimensions, including AUV performance, formation control, and communication capability. This framework provides a comprehensive classification method for future AUV formation research. It also can be used to compare different methods and help engineers choose suitable formation methods for various applications. Moreover, our survey discusses formation architecture with communication constraints and we identify some common misconceptions and questionable research for formation control related to communication.**

***Index Terms*—Autonomous underwater vehicle (AUV), communication constraint, network topology, formation control.**

## I. Introduction

APPROXIMATE 71 percent of the Earth's surface is water-covered and 97 percent of this water-covered surface is ocean water [1]. Moreover, 95 percent of the world's oceans and 99 percent of the ocean floor are still unexplored [2]. Knowledge from unexplored ocean is important. Revealing the secrets of deep-ocean ecosystems can discover new sources for medical drugs, food, energy resources, and other products. As a widely used tool of underwater exploration, Autonomous underwater vehicles (AUVs) receive a lot of attentions.

AUVs are submersible underwater vehicles that are driven by propulsion systems, powered by batteries or fuel cells, controlled and piloted by onboard computers. In recent years, with the advance of development of material science, computer hardware and control theory, AUVs are proven reliable and cost-effective while performing underwater tasks by comparison with manned submersibles and remotely operated vehicles [3]. Therefore, there has been a growing interest in applications of AUVs, not merely restricted to scientific underwater exploration [4], [5]. There are many underwater applications, such as military applications, hull inspection, fishing, etc., with the help of various sensors installed on AUVs.

However, in many situations, a single AUV is difficult to fulfill complex tasks in an unknown underwater environment [6], since ocean current and marine organism may break the AUV and limited power supply may also delay the mission. Therefore, to accomplish tasks with high efficiency and good stability, AUV formation control becomes a hot research topic. The idea of formation control is inspired by animal behaviors. Many animals benefit from moving as swarming [7], such as schooling or flocking. Through grouping, these animals can exchange information to find food or avoid enemies with more efficiency [8], [9]. Several definitions of 'formation control' are proposed in many papers [10], [11], [12], [13]. In this paper, formation control is defined as: 'Controlling a group of coordinated robots to achieve robots maintain predefined spatial pattern while performing a special task with a desired route.' Formation control aims to control relative position, velocity, and orientation of AUVs to conduct tasks while moving as a group.

To achieve formation control, AUVs need to exchange some critical information from each other through wireless communication. There are three main types of communication techniques: radio-frequency, optical, and acoustic communication. Due to the nature of underwater environments, acoustic communication is the most widely used technique [14], [15]. Acoustic communication can spread further than the other communication techniques [14]. Optical communication can

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TABLE I
COMPARISON OF THE RELATED SURVEYS ON AUV FORMATION WITH OUR SURVEY

| Survey | Topic(s) | Research Object(s) | Features | Weaknesses (Compared with the AUV formation topics) |
|---|---|---|---|---|
| [17] | Acoustic Communication | Sensors | A discussion about several practical issues, such as network operating regimes and energy efficiency | Lack of discussions about AUV formation applications |
| [21] | Acoustic Communication | Sensors | A comparative study of Medium Access Control (MAC) protocols based on several applications | |
| [19] | Acoustic Communication | Sensors | A short survey focuses on technique details, such as channel equalization and spatial modulation | |
| [22] | Acoustic/Optical Communication | Sensors/AUVs | A study about routing/MAC protocols and AUV-assisted networks | AUVs in AUV-assisted networks and AUVs in formation are totally different in AUV purposes and AUV control techniques |
| [23] | Acoustic Communication | Sensors/AUVs | A study about architectures and localization methods of underwater networks | |
| [24] | Acoustic Communication | Sensors/AUVs | Discussions and Classifications of underwater network applications | |
| [27] | Formation Control | Multi-agent Systems | A study focuses on consensus problems, including vehicle formation | Lack of underwater environments and communication problems |
| [28] | Formation Control | Multi-agent Systems | A classification method of formation control based on controlled variables | |
| [34] | Underwater Navigation | AUVs | A review of techniques of AUV navigation and localization | Focus on specific (non-formation related) aspects |
| [35] | Formation Control | AUVs | A review on cooperative search and formation control strategies for AUVs | Only mention communication constraints in future challenge parts |

provide high data rate at a close distance and can be used by AUVs for collecting data from fixed underwater sensors [16]. However, for AUV formation applications, short communication ranges have two flaws. First, if AUVs keep a close distance with each other, the risk of collision also increases. Second, advantages of formation techniques include expending sensing abilities and improving work efficiency of AUVs. If AUVs stay at a close distance, they cannot achieve the advantages well. Therefore, even though there are still many constraints (high propagation delay, path loss, noise, Doppler effect, etc.), acoustic communication is the most widely used in underwater [14].

Even though there are still some constraints, which can greatly affect the stability of the AUV formation, most studies in the literature of underwater acoustic communication only focus on sensor networks [17], [18], [19], [20]. In Table I, we list a series of surveys which have one or two related aspects with our survey. Several surveys summarize recent advances in underwater acoustic networks (UANs), including protocols, network architectures, localization schemes, etc. [17], [19], [21], [22]. Nevertheless, AUVs are totally different from underwater sensors. An AUV equips with propulsion system that can move fast may cause extra communication constraints, such as Doppler effect or self-generated noise. Moreover, an AUV can work as a underwater platform with various sensors for different purposes. AUVs may have better power supplies and stronger computing and communication capabilities than modems of sensors, but propellers' noise and Doppler effect indeed decrease communication quality.

Moreover, the surveys in [23] and [24] mention that AUVs can be employed in large-scale UANs to improve the network reliability. However, AUVs play totally different roles in AUV formation and AUV-assisted networks. In AUV-assisted networks, AUVs collect information from stationary nodes and rely the information to surface vessels or buoy nodes [25]. Therefore, AUVs can improve communication quality by shortening communication distance and are not limited by formation shapes. In AUV-assisted networks, the control techniques of AUVs mainly focus on AUV path planning since path planning influences network performance and energy consumption of AUVs [26]. In AUV formation fields, AUV formation mainly focuses on formation control techniques to achieve robust or adaptive control since AUVs need to keep a formation shape and cooperative with each other. For some formation tasks, AUVs need to keep as far apart as possible to expand their sensing abilities, such as searching a sunken vessel. Moreover, when AUV formation encounters obstacles, AUVs also need to change the formation shape to avoid the obstacles.

Furthermore, there are some surveys of multi-agents mainly focusing on control techniques while multi-agent can refer to multiple robots, vessels, or flights without a specific environment [27], [28], [29]. Formation applications of UAVs, USVs, or AUVs are also quiet different. UAVs are generally used for aerial photography, drone delivery, precision agriculture, and traffic monitoring [30]. USVs are mainly used for maritime search and harbor surveillance [31]. Applications of AUVs include: oil and gas industries, hydrographic surveys, and underwater telecommunication industry, etc. Communication methods of unmanned aerial vehicles (UAVs) or unmanned surface vehicles (USVs) are also different from AUV formation since UAVs or USVs can communicate with each other via base stations or satellites. These communication infrastructures offer a much better communication capability than underwater acoustic wireless communication [32], [33]. In addition, AUVs often cannot receive global positioning system (GPS) signals caused by underwater environments. In [34], the authors present a review of several commonly used techniques of AUV navigation and localization. Traditional techniques of AUV navigation are useful, but require predeployed and localized infrastructure (e.g., surface vessels or beacons). The simultaneous localization and mapping techniques, which are emerging techniques, can navigate an AUV without GPS signals at unknown places.

As discussed in the above, most studies focus on only one research topic of AUV formation. However, due to the limited underwater communication and AUV features, AUV formation becomes an interdisciplinary research. Typical formation control methods may not satisfy underwater environments since most of the methods are developed under some strong assumptions difficult to realize in underwater environments. Although a survey in [35] about AUV formation is presented, the paper still mainly focuses on control techniques and just mentions communication very briefly and the relationship between communication capability and formation control is lacking. We notice that some researchers try to tackle the AUV formation with communication constraints, but the researchers modeled the communication constraints with impractical assumptions and work toward to questionable research due to the interdisciplinary feature of AUV formation and lack of the related knowledge. To help researchers avoid impractical research, it is timely to survey AUV formation from an interdisciplinary view. In this paper, we provide a comprehensive survey of the state of the art in AUV formation research and development. In order to satisfy interdisciplinary audiences, we attempt to group together all the preliminary background aspects that a researcher should take into account before starting to work on AUV formation. Additionally, we try to point out questionable research to date and find the crucial gap between theoretical research and practical situations in AUV formation fields. Our main contributions are listed as follows.

- To the best of our knowledge, it is the first time in the literature to present an integrated survey on AUV formation to satisfy interdisciplinary audiences. We propose a classification framework with three dimensions, including AUV performance, formation control, and communication capability. This classification can help people for research and development of AUV formation.
- We study existing papers of AUV formation by combining knowledge in the field of communication and control. Moreover, we provide several suggestions to build feasible AUV formation.
- We summarize configurations of several outstanding AUVs and a list of modem products from several famous companies. This summary can show the difference between AUV communication and traditional underwater sensor communication.
- We identify some common misconceptions and questionable research for formation control related to communication. For examples, we point out that assuming a small bound delay is unrealistic and dangerous for underwater AUV formation control; reducing control information in half does not reduces the traffic in half at all and in fact it only decreases traffic in a tiny bit due to both the small length of control information and the larger overhead of headers of network protocols.
- We summarize and deeply discuss the mathematical models of AUV dynamics and communication constrains. Moreover, we point out the potential assumptions and limitations of the mathematical models.
- The main contribution of this paper is to provide both a tutorial and a survey for AUV swarm formation control system to satisfy interdisciplinary audiences as well as discussions on the main errors that people working on this topic do when evaluating the designed formation control system via analysis and simulations.
- Based on the purpose of designing practical AUV formation, we list several future research directions.

The rest of this paper is organized as follows. We introduce AUV and formation control as a background in Section II. In Section III, we classify AUVs, formation control, communication constraints, and network topologies, respectively. In Section IV, we discuss and analyze AUV formation with interdisciplinary considerations. Moreover, we identify several common misconceptions and questionable research. We study existing papers of AUV formation by combining knowledge in the field of communication and control. Future research directions and conclusions are presented in Sections V and VI, respectively.

## II. Background

In this section, we introduce AUV and formation control as a background.

### A. Autonomous Underwater Vehicle

In contrast to manned submersible vehicles and remotely operated vehicles, AUVs are untethered and automated submersible platforms. Untethered and unmanned features can reduce operational cost and human safety problems (e.g., mine reconnaissance). The first AUV was named Self-Propelled Underwater Research Vehicle (SPURV) and developed by University of Washington in 1957 [36], [37]. The SPURV has a shape like a torpedo. It can operate at depths up to 3000 meters and move about 2.3 meters per second for around 4 hours [38]. During recent 60 years, development of AUV techniques grows rapidly. In this subsection, we introduce some details of AUV techniques.

*1) Systems of an AUV:* AUVs can fulfill tasks without human operating since they can control and navigate themselves by computers and navigation systems. The essential information for these systems is obtained by onboard sensors from surrounding environments. Typically, most AUVs must have several basic systems, such as navigation systems, energy systems, and sensor systems, etc.

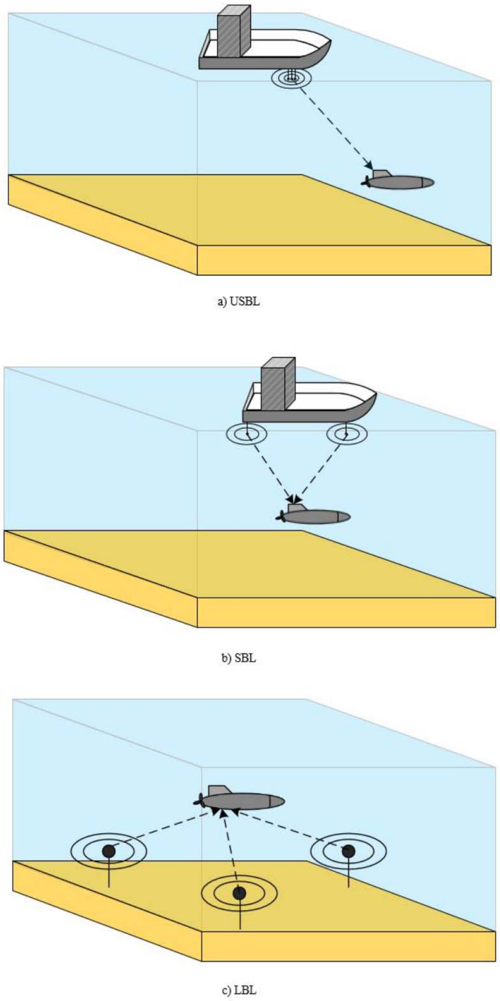



Fig. 1. Ultrashort Baseline (USBL), Short Baseline (SBL), and Long Baseline (LBL).

*Navigation System:* A navigation system is one of the most important systems of an AUV [39]. Navigation systems, including navigation techniques and navigation hardware, are presented as follows:

Navigation is a challenging problem in underwater due to the rapid attenuation of GPS signal. To overcome this problem, researchers propose a series of navigation techniques in the past decades [34], [40]. Some old techniques require predeployed and localized infrastructure (e.g., surface vessels or beacons). These techniques include ultrashort baseline (USBL), short baseline (SBL), and long baseline (LBL). USBL and SBL systems contain a surface vessel. A LBL system includes fixed beacons. A beacon is a device that guides AUVs by emitting repeated signals.

As shown in Fig. 1(a), a USBL system contains a transceiver and a transponder. A transceiver is a device that can both transmit and receive signals. In a USBL system, a transceiver includes three or more transducers that can produce signals and are separated by a baseline within 10 cm. The baseline is the distances among transducers. A transponder is a device that receives a signal and automatically transmits a different signal. The transceiver is installed under a surface vessel and the transponder is installed on an AUV. In order to calculate positions of an AUV, a USBL system measures relative directions and ranges from the surface vessel to the AUV. Relative directions are derived from phase difference of an acoustic signal at the transducer array. Ranges are calculated through measuring time of flight of the acoustic signal from transmitting to receiving [41].

A SBL system is similar to USBL, as shown in Fig. 1(b). One obvious difference between these two systems is that the baselines of a SBL system are longer than those of a USBL system. For a SBL system, relative directions can be determined by measuring signals' time of arrival (TOA) of different transducers. USBL systems do not use TOA measurements since their ultra-short baselines require additional accuracy for TOA measurements.

As shown in Fig. 1(c), for a LBL system, three or more fixed beacons are widely installed on the seabed. An AUV can obtain localization within the area of beacons by triangulating acoustically determined ranges.

Several advanced technologies that allow for rapid deployment and flexibility with the minimal infrastructure are proposed by researchers [34], such as cooperative navigation (CN) and simultaneous localization and mapping (SLAM).

A CN system can obtain location information for an AUV group through communication and detection among each other [42]. In a CN system, AUVs are all equipped with detection sensors for relative range and direction measurements. Each AUV in formation exchanges its information from detection sensors with other AUVs to improve localization precision. CN systems can be classified into centralized and decentralized systems based on different sensor deployment strategies [43]. In a centralized system, a typical situation is leader-follower cooperative navigation, including a leader AUV and a follower AUV at least. The leader AUV is equipped with a high accuracy navigation system, whereas the follower AUVs are equipped with low accuracy and low reliable navigation systems. The follower AUVs calculate their locations based on the information from the leader AUV. In a decentralized system, all of the AUVs are equipped with the same performance detection sensors. Each AUV calculates its locations based on the information from the other AUVs in the group.

SLAM techniques enable an AUV navigate without GPS signal at unknown places [44]. While moving in unknown environments, the AUV incrementally builds a consistent map. The AUV can localize itself by measuring the distance from landmarks of the map [45]. Up to now, many SLAM solutions are proposed by researchers [34], such as extended Kalman filter (EKF) SLAM [46], Sparse extended information filter (SEIF) SLAM [47], FastSLAM [48], GraphSLAM [49], and artificial intelligence (AI) SLAM [50]. EKF-SLAM, SEIF-SLAM, and FastSLAM are based on different filters. GraphSLAM is based on graph theory. Nodes of a graph correspond to poses of AUVs during mapping and edges correspond to spatial constraints between two AUVs. AI-SLAM uses techniques of fuzzy logic and neural networks.

To support navigation technologies as we discussed above, the navigation system of AUVs consists of a number of hardware:

- Compass [51]: This instrument is used to provide directions relative to the geographic cardinal directions. There are two kinds of compasses: magnetic compasses and gyro-compasses. Magnetic compasses are the most common compass types. Pointers of magnetic compasses point to magnetic north, whereas pointers of gyro-compasses point true north or geographical north. In contrast to magnetic compasses, gyro-compasses have one major advantage that they are not affected by wires with electric current or ferromagnetic mental in a vehicle's hull.
- Pressure sensor [52]: This device is used to measure underwater pressure. In addition, it can calculate the depth of the AUV location.
- Doppler velocity log (DVL) [53]: A DVL is a device that measures velocities under water. A DVL transmits acoustic waves downward in various directions and receives echoes from seabed. The movement of AUVs generates the Doppler Effect, which changes frequencies and phase of echo waves. Combining these readings can calculate velocities of an AUV.
- Sonar [34]: A Sonar is used to detect or locate objects with acoustics. Sonars can be classified into passive sonars and active sonars. Active sonars emit specific acoustic waves and receive echoes, whereas passive sonars receive sounds from other objects. Additionally, active sonars can be further classified into imaging sonars and ranging sonars. Imaging sonars produce images of ocean floor and ranging sonars produce bathymetric maps.
- Inertial navigation unit (INU) [54]: An INU includes a computer, accelerometers, and gyroscopes. This device can continuously estimate vehicle's ranges, orientations, and velocities by dead reckoning. Dead reckoning is a method of estimating the location of an AUV based on its previous location, course, speed, and a known interval of time.
- GPS: GPS can provide location and time information when AUVs surface. A navigation method is that AUVs obtain GPS signals by surfacing periodically.

*Communication System:* AUVs equip with acoustic modems for underwater communication. Acoustic modems transmit and receive sound signals by converting electrical energy into acoustic energy and acoustic energy into electrical energy. Modem manufacturers make efforts to improve communication reliability and increase data throughput. For example, a) some manufacturers adopt spread-spectrum techniques to increase packet delivery ratio in multipath environments, resulting in higher throughputs in those scenario because they limit the need of re-transmissions; b) increasing time delays between frames reduces the interference from multipath. In order to have an overview about features of acoustic modems, we summarize a series of up-to-date modem products from different manufacturers, as shown in Table II. Table II can provide information for designing AUV formation in practice, especially about designing AUV distance, formation shapes, and communication topologies. First, Table II indicates that the most modems can offer horizontal communication within 3 km working ranges in good conditions. Modems have different working ranges correspond to different transmission directions. When researchers design AUV formation, they need to consider that AUV formation ranges are not only limited by working ranges of modems, but also depend on different AUV altitudes. Second, AUVs need to exchange information including control commands, navigation information, and environment information. Some researchers attempt to decrease the overhead of control commands to overcome limited bandwidth [55], [56], [57]. Bandwidth and data rate in Table II can provide a reference to determine whether decreasing control commands is necessary. The S2CR, S2CM, and S2CT are different product series. The S2CR-series are standard and highly configurable series. To satisfy different specific applications, the S2CR-series can provide a large selection of options and depth ratings. The S2CM- and S2CT-series have light and compact designs for size-limited or weight-sensitive devices. The S2CM-series is available for high- and mid- frequency transducers. The S2CT-series is available for high frequency transducers.

*Energy System:* Most energy systems of AUVs are batteries. Traditional battery types are lead-acid and silver-zinc batteries. A lead-acid battery is cheaper than a silver-zinc battery, whereas the latter one can offer double energy than the former [58]. Nowadays, lithium batteries are widely used in AUVs, as well as mobile phones or laptops. Lithium batteries are rechargeable. This feature can greatly reduce cost. However, shortage of battery life is still a limitation. To overcome this limitation, some AUVs can equip with replaceable batteries so that people can change batteries and allow AUVs back to work rapidly.

*Functional Sensor Systems:* AUVs can work as sensor platforms to equip with various sensors. Sidescan sonars, 2D/3D image sonars, synthetic aperture sonars, and digital cameras can be used to create images. Sub-bottom profilers and multi-beam sonars are equipped for swath bathymetry seafloor mappings. Echo sounders and underwater laser scanners can be used to measure ranges. Forward looking sonars can be used to avoid obstacles. A conductivity temperature depth can be used to measure the conductivity, temperature, and pressure of seawater. To date, an increasing number of sensors are designed for meeting various missions.

*2) Applications:* Applications of AUVs can be roughly categorized into civilian and military applications. Civilian applications include oil and gas industries, telecommunication industry, security of shipping, hydrographic survey, and fishing. For oil and gas industries, AUVs play significant roles in the respects of acoustic inspection of pipelines, sub-sea installations, and various surveys (i.e., geo-hazard/clearance, rig site, pipeline route and construction site surveys) [59]. For telecommunications industry, AUVs also can be used to survey route, collect data of seabed, and lay submarine cable [60], [61]. With increasing attentions to the security of shipping, AUVs are applied to field of hull inspection [62], [63], [64]. Hydrographic survey is

TABLE II
PROPERTIES OF UNDERWATER ACOUSTIC COMMUNICATION MODEM PRODUCTS

| Type Name | Transducer Beam Patterns | Working Range | Frequency Band (kHz) | Data Rate (bps) | Bit Error Rate | Manufacturer |
|---|---|---|---|---|---|---|
| ATM-903 | 60/70/180 degrees | 2-6 km common, greater distances possible over 20 km available using repeater functionality | 9-1 (LF); 16-21 (MF); 22-27 (Band C) | 80-15360 | Unknown | Teledyne Marine www.teledynemarine.com |
| ATM-915<br>ATM-916<br>ATM-925<br>ATM-926<br>ATM-965<br>ATM-966 | | | | 140-15360 | Less than $10^{-7}$ | |
| UWM1000 | Near-vertical or horizontal environments 70/120/210 degrees | Up to 0.35 km | 26.77-44.62 | 9600-19200 | Less than $10^{-9}$ | LinkQuest Inc. www.link-quest.com |
| UWM2000 | Near-vertical or horizontal environments 70/210 degrees | 1.2 km (omni-directional) 1.5 km (narrow beam) | 26.77-44.62 | 9600-192000 | | |
| UWM2000H | Long-range shallow to very shallow water environments 70/210 degrees | | | 300-1200 | | |
| UWM2200 | Near-vertical or horizontal environments 90 degrees | Up to 1km | 53.55-89.25 | 19200-38400 | | |
| UWM3000 | Near-vertical or horizontal environments 210 degrees | 3 km/5 km | 7.5-12.5 | 2500-5000 | | |
| UWM3000H | Long-range shallow to very shallow water environments 210 degrees | | | 80-320 | | |
| UWM4000 | Near-vertical or horizontal environments 70 degrees | 4 km | 12.75-21.25 | 4800-9600 | | |
| UWM10000 | Near-vertical or horizontal environments 70/210 degrees | 7 km (omni-directional) 10 km (directional) | 7.5-12.5 | 2500-5000 | | |
| GPM300 | Unknown | Up to 25 km | Unknown | Up to 1200 | Less than $10^{-4}$ | L3 Oceania www2.l3t.com/oceania |
| WHOI Micro-Modem | Unknown | 2.5-18 km | 10-25 | 80-5400 | Unknown | Woods Hole Oceanographic Institution www.whoi.edu |
| S2CM 18/34<br>S2CR 18/34<br>S2CR 18/34D | horizontally omnidirectional | Up to 3.5 km | 18-34 | Up to 13900 | Less than $10^{-10}$ | EvoLogics GmbH www.evologics.de |
| S2CR 18/34H | hemispherical (horizontal/vertical/slant) | | | | | |
| S2CT 42/65 | wide-angle 100 degrees (horizontal/vertical/slant) | 1.5 km in good conditions | 42-65 | Up to 31200 | | |
| S2CM 42/65<br>S2CR 42/65 | | Up to 1 km | | | | |
| S2CM 48/78<br>S2CR 48/78 | horizontally omnidirectional | Up to 1 km | 48-78 | 31200 | | |
| S2CM HS | omnidirectional | Up to 0.3 km | 120-180 | 62500 | | |
| S2CR 15/27 | 120 degrees vertical/slant transfer to/from stationary systems | Up to 6 km | 15-27 | Up to 9200 | | |
| S2CR 12/24 | 70 degrees vertical/slant transfer to/from stationary systems | Up to 8 km | 13-24 | | | |
| S2CR 7/17 | hemispherical vertical/slant transfer to/from stationary systems | Up to 8 km | 7-17 | Up to 6900 | | |
| S2CR 7/17W | hemispherical slant transfer | | | | | |
| S2CR 7/17D | 80 degrees vertical/slant transfer | Up to 10 km (for vertical transfer) | | | | |

another significant application since AUVs present outstanding performance of oceanographic mapping, sampling network, and analyzing water quality [65], [66], [67], especially in some extreme environments, such as under ice or in deep sea [68], [69]. Fishing and fishing farming become an emerging market of AUV applications. AUVs can be used to clean aquaculture nets, monitor and protect spawning area of fishes, and observe fishery resources [70], [71], [72].

There are some military applications, such as mine countermeasures, mine reconnaissance, and depth independent mine detection and localization [73], [74], [75], [76]. With advanced sensors, AUVs may be used in extra military applications such as intelligence, surveillance, rapid environmental assessment, and anti-submarine warfare.

### B. Formation Control

In the last decades, AUVs rapidly emerge as essential tools for underwater applications. Nevertheless, underwater environments are hostile. Unknown ocean floor and sea current may break an AUV. Additionally, mystery thermals can also cause AUVs in trouble at work. To improve these situations, formation control of AUVs is an important technique that can fulfill tasks with better flexibility, adaptability, and scalability [77]. The purpose of formation control is controlling relative range, velocity or orientation of AUVs to move as a group. Next, we present some details about formation control.

*1) Problems:* Typically, formation control includes three problems [78]: a) formation acquisition indicates that AUVs move from initial locations to desired locations in order to achieve a particular geometric shape; b) formation maintenance focus on maintenance of an achieved geometric shape of AUVs during fulfilling tasks; c) formation reconfiguration is a series maneuvers (e.g., translation, rotation, expansion, and contraction) that can change formation shape as a reaction to task requirements, such as avoiding obstacles or passing through narrow passages.

*2) Architectures:* Architectures of formation are kinds of logical and physical models, which should consider information and control relationship among AUVs members [79]. Architectures are basic issues of cooperative formation since architectures determine the capabilities and limitations of AUVs. There are several aspects that have significant impacts on architecture design, such as task decomposition, task allocation, role assignment, inter-AUV interference, AUV cooperation, conflict resolution, negotiation, and inter-AUV communication, etc. [80].

*3) Control Strategies:* In order to satisfy various missions, different formation strategies are proposed by researchers to achieve better formation [81]. Most existing formation control strategies can be classified into leader follower strategies, behavior-based strategies, virtual structure strategies, graph theory-based strategies, and artificial potential function strategies. These strategies can also be mixed together [82]. We give a further introduction and comparison about these formation control strategies in the next section.

*4) Controllability Analysis:* Formation controllability is defined as it is possible to maneuver a formation system from an initial state to an anticipative state [83]. Controllability is a fundamental issue of formation control. So far, most significant methods of controllability analysis are based on graph theory and Lyapunov function [77].

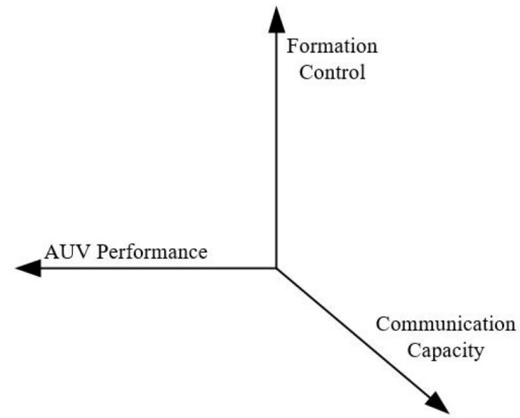



Fig. 2. Classification Frame.

*5) Applications:* Moving in formation has many advantages over traditional systems since formation can expand sensing ability, reduce system cost, improve reconfigurability, and increase overall system robustness and efficiency. Up to now, formation techniques are applied to many fields. For spacecrafts or satellites, formation can keep each agent stay in a stable distance that can share signal processing and exchange information [84]. For unmanned aerial vehicles, formation can overcome payload limitation of a single aerial vehicle. In addition, aerial vehicle formation is widely used in many applications, such as surveillance and searching objects, etc. [85]. For AUVs, formation control is also an attractive topic for various applications. However, AUV formation control still stay in an early stage due to limited underwater communication capability. We have a further discussion about communication capability in the next section.

## III. Classification

AUV performance, formation control, and communication capability are all important for achieving better AUV formation. We propose a classification framework with three dimensions, including AUV performance, formation control, and communication capability, as shown in Fig. 2. The goals of our classification framework includes: a) to provide a comprehensive classification method for future AUV formation research; b) to compare different methods and help engineers choose suitable formation methods for various applications.

In this section, first, we classify AUVs based on body shapes. Second, we categorize formation control based on architecture, control strategies, and controllability. Third, we classify communication capability based on communication constraints and network topologies. Finally, we survey formation control and communication capability together.

### A. Classification of AUVs

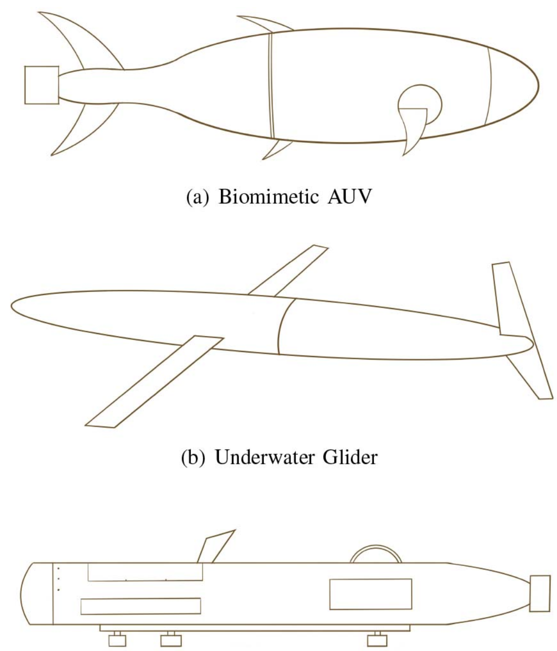
For AUV formation control, AUV performance is a key factor which should be considered in practice. In order to meet various purposes, a lot of shapes of AUVs are designed by different manufacturers. AUVs can be classified by body shapes, application purposes, manufactures, or body scales. Classification of AUVs based on body shapes is the most

TABLE III
EXAMPLES OF SEVERAL OUTSTANDING CURRENT AUVS [86]

| Body Shape | AUV Type | Weight (kg) | Maximum Depth (m) | Speed (m/s) | Endurance (hours) | Manufacturer |
|---|---|---|---|---|---|---|
| Biomimetic AUV | MantaDroid | 0.7 | Unknown | 0.7 | 10 | National University of Singapore |
| | Auqa2 | 16.5 | 30 | 0.51 | 5 | Independent Robotics Inc. |
| | Naro Tartaruga | 75 | 100 | 2 | Unknown | ETH Zurich Autonomous Systems Laboratory |
| | BioSwimmer | 40.8 | 100 | 2 | 14 | Boston Engineering |
| Underwater Glider | Seaglider | 80 | 1000 | 0.25 | 7200 | Kongsberg Gruppen |
| | Slocum | 50-70 | 150-1000 | 0.35-1 | 360-12960 | Teledyne Technologies |
| | Seaexplorer | 59 | 1000 | 0.25 | 1536-3840 | Alseamar |
| Torpedo Shape AUV | SeaCat | 130-220 | 600 | 3 | 10-20 | Atlas Elektronik GmbH |
| | ISE Explorer | 620-1700 | 3000-6000 | 0.5-2.5 | 24-85 | International Submarine Engineering Ltd. |
| | AUV62-AT | 800 | 300 | 1.5-6 | 3-18 | Saab AB |

appropriate compared to the other three classifications. The reasons include: a) most AUVs have more than one application purposes and they can perform several applications at the same time during a task; b) classification based on manufactures or body scales is less useful and lack of classification features. Based on AUV shapes, an AUV website classifies AUVs into more than ten types [86]. However, the classification in the [86] is redundant and not distinct enough. For example, teardrop shape AUVs and model-submarine shape AUVs are similar to torpedo shape AUVs. Moreover, the classification in the [86] does not describe any features about each AUV type. To classify a new AUV, it is difficult to follow the classification in [86]. To come up with a classification that is concise and easy to implement for a new AUV, we categorize AUVs into biomimetic AUVs, underwater gliders, and torpedo shape AUVs based on their body shapes.

- Biomimetic AUV: Inspired by real sea creatures, some AUVs are designed like fishes or turtles, as shown in Fig. 3(a). To reach high-endurance, their hull shapes are designed for drag reduction and course keeping [87]. Moreover, they usually have several independently controlled fins to achieve high maneuverability in harsh environments [88]. Due to high maneuverability of Biomimetic AUVs, they are used in some complex applications, such as hunting mine, conducting intelligence, and inspecting hull.
- Underwater Glider: As shown in Fig. 3(b), an underwater glider has a pair of wings. When gliders work in water, especially in shallow water, currents and waves make gliders up and down. Wings of gliders can convert vertical motion to horizontal motion. The above mechanism is called buoyancy-based propulsion. Due to buoyancy-based propulsion, gliders have long endurance at a slow speed. Some gliders (e.g., Bluefin Spray Glider, Scripps Spray Glider) can work several months. Underwater gliders are widely used in ocean observation fields since these fields need gliders with high endurance. Moreover, buoyancy-based propulsion has another advantage that gliders can move stealthily with very low self-noise [89].



(a) Biomimetic AUV

(b) Underwater Glider

(c) Torpedo Shape AUV

Fig. 3. Classification of AUVs.

- Torpedo Shape AUV: Torpedo shape AUVs shown in Fig. 3(c) are the most common products of AUVs. Torpedo shape AUVs can be built very large so that they can equip with a complete sensor system. Due to various functions of sensors, torpedo shape AUVs are widely used in a vast field and receive a lot of attentions. Up to now, more than a hundred kinds of torpedo shape AUVs are developed [5].

AUVs have several significant features, such as speed, endurance, and operational depth. In order to present further details about these features of different shape AUVs, we summarize several outstanding AUVs from manufacturer websites in Table III. From Table III, we observe: a) to satisfy various tasks, torpedo shape AUVs have balance performance and

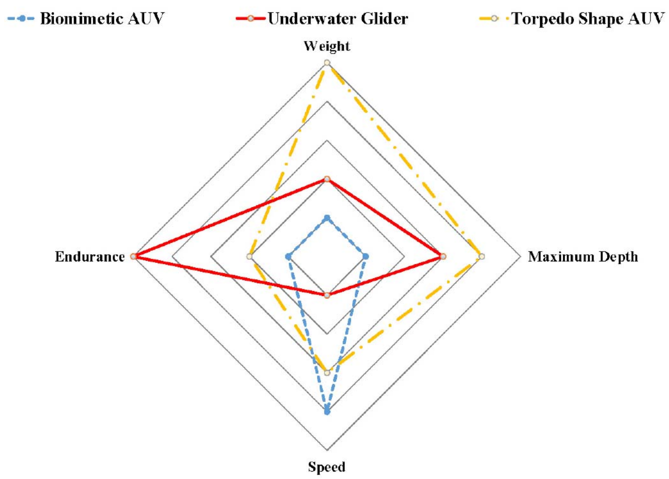



Fig. 4. An Comparison of AUV Features.

can be built very large with various equipment; b) although underwater gliders have relative slow speeds, their extremely high endurance guarantees that they can travel thousands of kilometers in a single deployment; c) biomimetic AUVs are lightweight and can move fast as well as torpedo shape AUVs, but most of them work at nearly shallow water; d) the light weight of gliders and biomimetic AUVs is cost-effective since they can be launched from a small vessel by only one or two people, inducing deployment costs. As shown in Fig. 4, we summarize above features into a radar graph to provide an intuitive sense among different shapes of AUVs.

### B. Classification of Formation Control

After an introduction of formation control techniques in Section II, we classify formation control techniques based on architecture, strategy, and controllability.

*1) Architectures:* Architectures of AUV formation can be classified into centralized and decentralized architectures. The decentralized architectures include distributed and hierarchical architectures. The major difference of three architectures is decision-making process, which can be regarded as processes of action selections [90]. In centralized architectures, shown in Fig. 5(a), a central controller has global information about all AUVs and environments. The global information (e.g., AUV locations and speeds, obstacle locations) is collected by AUV sensors. In order to make an AUV swarm keep a predefined shape, avoid obstacles, and arrive destination, a centralized controller processes the global information and determines decision-making [91]. Then a centralized controller transmits command signals to each AUV while each AUV transmits their state information to a centralized controller (e.g., a leader AUV) as a feedback [92]. The main advantage of centralized architectures is easy and simple to implement, whereas the disadvantages include: a) weak robustness with respect to the fault of the centralized controller; b) lack of scalability due to limited communication ranges. In distributed architectures, shown in Fig. 5(b), AUVs can exchange information of environments and/or AUV states. To achieve distributed control, each AUV needs to share its information with a subset AUVs of the whole swarm. Each AUV has a controller that can make

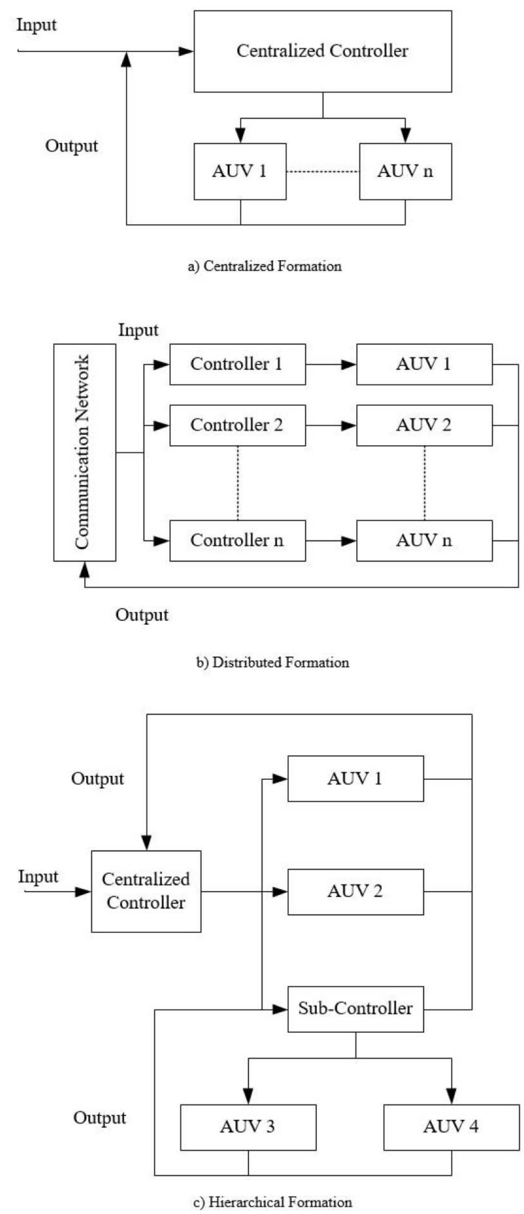



Fig. 5. Formation Architectures.

decision independently based on local information of the AUV swarm [93], [94]. For example, an AUV can maintain the same speed and a constant distance with its neighbor AUVs only based on speed and location information from its neighbors [57], [95]. Thus, formation maintenance achieves since each AUV keeps synchronization with its neighbor AUVs. The advantages of distributed architectures include: a) better robustness and scalability than centralized architectures; b) sharing computing and communicating burden with each AUV. In hierarchical architectures, shown in Fig. 5(c), there exist one or more sub-controllers which organize AUVs into clusters. The hierarchical architectures can be regarded as an extension of centralized architectures. The centralized controller makes decisions and gives commands to sub-controllers. Then sub-controllers process commands from the centralized controller and transmit new commands to their own cluster.

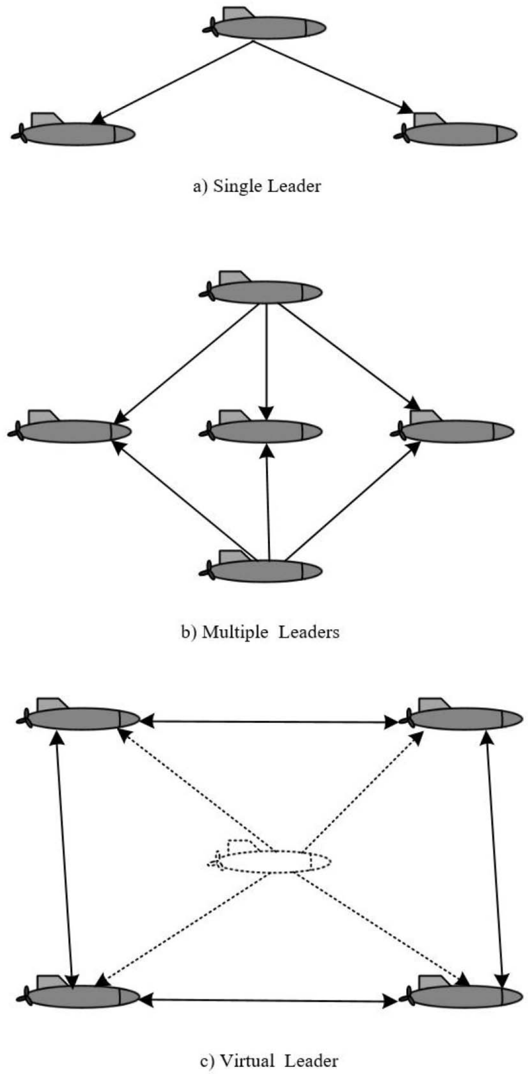



Fig. 6. Leader Follower Strategy.

AUVs in each cluster execute commands and give feedbacks to their sub-controllers while sub-controllers also give feedbacks to the centralized controller [96], [97], [98]. The advantages of hierarchical architectures include: a) high scalability; b) sharing computing and communicating burden with sub-controllers. A disadvantage of hierarchical architectures is lack of robustness with respect to failures of the centralized controller. The mentioned above disadvantages are relative and can be overcome by good designs.

*2) Formation Control Strategies:* Most existing formation control strategies can be roughly categorized into leader follower strategies, behavior based strategies, virtual structure strategies, graph theory based strategies, and artificial potential function strategies.

In leader follower strategies, one or more AUVs serve as leaders and others act as followers. The followers track the locations and the orientation of the leaders to achieve formation [99]. Up to now, many kinds of leader follower strategies are proposed [93], [100], [101], such as single leader strategies, multiple leader strategies, and virtual leader strategies, etc., as shown in Fig. 6. A single leader strategy has only one leader with one or more followers. A multiple leader strategy has two or more leaders and each leader has at least one follower. In contrast to a single leader, multiple leaders can achieve good performance of formation maintenance [93]. A virtual leader strategy allows AUVs to follow a virtual leader [100]. A virtual leader can be regarded as a moving reference point for the whole formation. The virtual leader has a predefined trajectory, which is also the desired trajectory of the whole formation. In order to maintain formation, the other AUVs keep a constant distance with the virtual leader while AUV formation moves to a destination. An advantage of leader follower strategies is that designs of controllers are simple since entire movement of formation is determined by a leader or leaders. A disadvantage is that these strategies are not robust enough since followers do not communicate with each other. If the/a leader fails, the entire formation fails.

In behavior-based strategies, several desired behaviors are designed for each AUV. Each behavior has its own purpose, such as move-to-goal, avoid-static-obstacle, avoid-AUV, and maintain-formation [102]. Behaviors-based controllers work as a structured network of these behaviors and decide which behaviors should be run together [102]. An advantage of behavior-based strategies is that little information needs to be exchanged among AUVs. Disadvantages include: a) design of basic behaviors and planning of local control are difficult; b) good stability of formation control cannot be guaranteed.

In virtual structure strategies, a group of AUVs are considered as a rigid structure. AUVs in a virtual structure strategy maintain a geometric shape with fixed relative ranges and bearing [103]. Achieving virtual structure strategies needs three steps. First, a desired dynamical behavior for a virtual structure is defined. Second, the desired behavior of virtual structure is translated into desired motions of each AUV. Finally, tracking controllers of AUVs are designed based on desired motions of each AUV. Advantages of virtual structure strategies include: a) coordinated behaviors of AUVs are easy to be described; b) the rigid structure has a good performance of maintaining formation. A disadvantage is that the virtual structure strategy has poor adaptability and flexibility.

Graph theory-based strategies include two kinds of graphs: undirected graphs and directed graphs [104]. In both graphs, a node is represented as an AUV. In an undirected graph, a length of an edge is represented as the distance between two AUVs. In a directed graph, If any AUV has an impact on another AUV (for instance the state of a AUV depends on the state of another AUV), there exists a directional edge between them. In both graphs, when the formation shape of nodes can represent the formation shape of AUVs. An advantage of graph theory-based strategies is that the well-developed graph theory can provide sufficient theoretical support for formation control. Disadvantages are that designing and solving a graph theory-based strategy are more complex than other strategies.

Artificial potential function strategies assume that AUVs move in an abstract artificial potential field, which includes a repulsive potential field and an attractive potential field. In potential fields, movements of AUVs depend on a potential force. Desired locations generate an attractive potential force that makes AUVs toward to desired locations. An obstacle generates a repulsive potential force, which is inversely proportional to the distance between an AUV and an obstacle. This repulsive potential force makes AUVs away from an obstacle. Potential energy, a property of a system, depends on relative positions between two objects (e.g., an obstacle and an AUV). A relation between a potential force and potential energy is similar to a relation between gravity and gravity potential energy. If the potential force makes AUVs move, the potential energy decreases. Movements of AUVs can be regarded as moving a formation from a high-value energy state to a low-value energy state. The potential energy of a field can be presented as artificial potential functions, including attractive potential functions and repulsive potential functions. The artificial potential function strategies have several advantages, such as simple calculation and easy implementation of real-time control. A disadvantage is that finding the local minimum value is difficult [105].

*3) Controllability:* Controllability is a significant property of a dynamical system. A dynamical system is controllable if there exists a controller that can transform the system's current state/output to a desired state/output in a finite time interval [106]. For formation control systems, it is important and necessary to determine whether the systems have controllability. Only when AUV formation is controllable, the formation can achieve a series of formation purposes, such as formation acquisition and formation reconfiguration. Next, we introduce two controllability analysis methods based on graph theory and Lyapunov functions.

Graph theory can be used to analyze controllability of a formation system. A formation system can be modeled by state space, which is a mathematical model of a system as a set of input, output, and state associated by differential equations in control engineering. Then state space can be described by a graph [107]. The characterization of the topology of a graph can be used to analyze system controllability and determine whether the control law, transferring any given initial state to the origin in a finite time interval, can exist. There are a number of papers about how to address controllability issues based on graph theory [106], [108], [109], [110].

The Lyapunov method is inspired by a physical idea that energy of an isolated system decreases with time. Lyapunov functions are auxiliary functions that used by the Lyapunov method. Controllability analysis via Lyapunov functions is a method that converts a formation control problem into a stabilization problem [111]. As the aforesaid definition of controllability, suppose that a system is stable at an equilibrium point and define the equilibrium point as the origin. A Lyapunov function is a positive definite function of the system states and the function can be regarded as the energy stored in the system. If the derivative of the Lyapunov function along the trajectories of the system is negative definite, the system state can stay sufficiently close to the equilibrium point and the system energy is dissipated. If researchers can construct proper Lyapunov functions, they can verify that the controller can transfer any given initial state to the origin. A main assumption of the method is that each AUV has its own Lyapunov functions. This assumption is that each AUV is stable and controllable. Based on the assumption, there exists a Lyapunov function for entire formation, which is a weighted sum of individual Lyapunov functions of each AUV. A Lyapunov function for entire formation can determine if a system is stable or not based on whether this function can find an equilibrium point [112]. The equilibrium point, regarded as a solution of a system, indicates that a dynamic system can stay at this point forever [113].

### C. Classification of Communication Constraints

To achieve AUV formation, AUVs need to exchange some critical information from each other through wireless communication. In underwater environments, acoustic communication has less attenuation than radio and wireless optical communications [114], [115]. With the same power consumption and antenna cost, less communication attenuation provides longer communication ranges. Acoustic communication is the most widely used technique in AUV formation fields [14]. However, underwater acoustic communication still has a series of nature constraints including variable propagation delays, ambient and self-generated noises, path loss, limited bandwidth, multipath, and Doppler effect [116], [117]. We explain the above constraints as follows.

*1) Propagation Delay:* In underwater environments, propagation delays are mainly caused by slow and variable propagation speeds [118], [119]. Most researchers normally assume that propagation speeds of acoustic waves are about 1500 meters per second in underwater environments (commonly between 1450 meters per second to 1550 meters per second) [120], which are five orders of magnitude lower than propagation speeds of electromagnetic waves in air. In practice, propagation speeds of underwater acoustic waves are affected by several environment factors, such as temperature, depth, latitude, salinity, etc. [121]. To calculate propagation speeds in water, the authors in [122] propose a propagation speed model endorsed by United Nations Educational, Scientific, and Cultural Organization. However, the above model is not accurate enough at low temperatures (0 °C to 15 °C) and high pressures (300 to 1000 bar) [123]. To fix the above deficiencies, the authors in [121] propose and verify a new simplified equation for the accurate calculation of propagation speeds based on temperature, salinity, latitude, and depth.

Above discussion explains features of propagation speeds and these features cause larger and time-varying propagation delays. Therefore, understanding propagation delays is helpful for designing better formation controllers. The authors in [124], [125] assume that propagation delays are constant and verify that their AUV formation can tolerate constant delays with robust formation controllers by simulations. However, propagation delays are large and time-varying in practice [126] so that the controllers in [124], [125] may be not robust enough in real underwater environments. How to tolerate large and time-varying delays to achieve better AUV formation is a significant question and still not fully resolved.

*2) Noise:* Noises have a significant impact on quality of communication. As shown in Fig. 7, noises can be classified

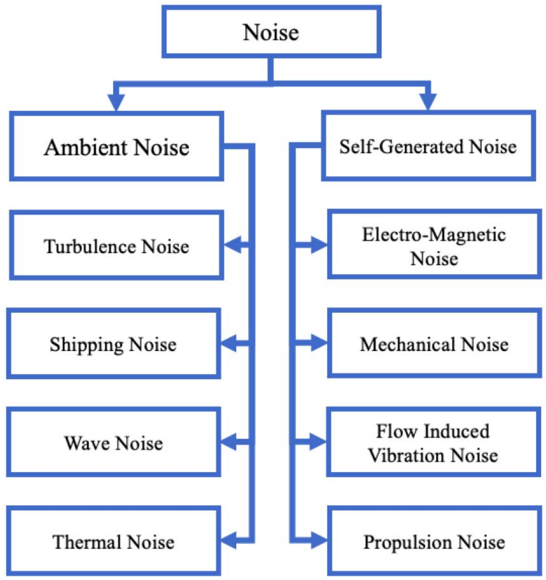



Fig. 7. Classification of noise of communication among multiple AUVs.

TABLE IV
AMBIENT NOISE

| Sources of Noise | Frequencies of Noise |
|---|---|
| Turbulence | Under 10 Hz |
| Shipping | 10 Hz-100 Hz |
| Wave | 100 Hz-100 kHz |
| Thermal | Over 100 kHz |

into self-generated noises and ambient noises in AUV communication fields. Self-generated noises are kinds of noises from AUVs themselves, such as electro-magnetic noises, mechanical noises, and flow-induced vibration noises [127]. The authors in [127] conduct research on that AUV self-generated noises interfere with onboard acoustic sensors. Ambient noises mainly include four types: turbulence, shipping, sea-wave, and thermal noises. According to [128], four ambient noises can be summarized based on frequency ranges, as shown in Table IV.

In some situations, noises may be useful. The authors in [129] attempt to detect locations of AUVs from a surface vessel by utilizing self-generated noises of AUVs. However, in AUV formation fields, noises should be considered as a negative factor since quality of communication is important for AUV formation. In typical underwater sensor communication fields, researchers mostly consider ambient noises. However, in AUV communication fields, the AUV self-generated noises should attract much attention. To date, several researchers characterize AUV noises [127], [129], [130]. The authors in [127] present a research about AUV self-generated noise spectra and levels. In order to detect AUVs by utilizing self-generated noises of AUVs, the authors in [129] quantify the propulsion noise levels and beam patterns from an underway AUV. The authors in [130] measure the AUV noises through a receiving hydrophone when an AUV moves at a speed of 2 meters per second from a distance of 500 meters to 50 meters. The authors in [130] point out that the AUV noise mainly contribute to the lower frequency band (<15kHz) at the distance from 500 meters to 50 meters, but the high frequency contribution increases when the AUV closes to the receiving hydrophone. For AUV formation, the noise problems are more complex than the above previous research. An onboard modem of an AUV in formation can be interfered with both noises from other AUVs and their own noises. Additionally, decreasing communication distances can increase communication quality in general situations, but noise impacts also increase in AUV formation. There is a need for further research about how to find an optimal AUV distance in formation based on communication quality and formation scale. Many researchers focus on how to decrease noises. In [131], the authors attempt to reduce noises through optimizing electric motor configurations. Reduction gears are improved by the authors in [132] for decreasing AUV self-generated noises. After improving reduction gears, the experiment results in [132] show that communication ranges are enhanced 2.5 times longer than before. The authors in [133] focus on lowering the levels of AUV self-generated noises below the levels of ambient noises and they also propose several methods (e.g., tail cone replacement) to decrease AUV noises. The authors in [134] use Gaussian white noise to model ocean noises and they attempt to eliminate noises by effective communication topology weights.

*3) Path Loss:* When a signal propagates, the signal energy spreads and is absorbed by mediums. The above process is called path loss [135]. For underwater acoustic communication, acoustic path loss $A(l, f)$ can be expressed in dB by the formula [136]:

$$10 \log A(l, f)/A_0 = 10k \log l + 10l \log a(f) \quad (1)$$

where $A_0$ is a unit-normalizing constant, $l$ is the distance between a transmitter and a receiver, $k$ is a spreading factor, $f$ is a sound frequency, and $a(f)$ is an absorption coefficient.

In equation (1), the first term $(10k \log l)$ presents spreading loss and the second term (10llog$a(f)$) presents absorption loss. Geometries of propagation can be described by the spreading factor $k$. For deep water communication, geometries of propagation are cylindrical spreading (omni-directional point source), where $k = 1$. For shallow water communication, geometries of propagation are spherical spreading (horizontal radiation only), where $k = 2$. However, geometries of propagation usually are hybrids of cylindrical and spherical spreading in practice, where $k = 1.5$ [136]. The absorption coefficient $a(f)$ can be calculated by Trop's formula [137], presenting a relationship between path loss and frequencies. In contrast to high frequency sounds, path loss of low frequency sounds is less [138]. The authors in [139] point out that less path loss can achieve a long communication range. For example, ultra low frequency (i.e., from 0.3 to 3 kHz) sounds even can achieve communication over 100 miles due to less path loss.

*4) Limited Bandwidth:* In underwater environments, available bandwidth of an acoustic channel is limited [140]. For various purposes, AUVs need to exchange much information, such as sensor data, control data, navigation data, etc. To properly allocate bandwidth, researchers should have a knowledge of available bandwidth. Up-to-date available bandwidth of different communication ranges is summarized based on [141] and [142] and is shown in Table V. However, data

TABLE V
BANDWIDTH WITH COMMUNICATION RANGE

| | Communication Range | Available Bandwidth | Data Rate |
|---|---|---|---|
| Long Range | Around 20 km | 2-3 kHz | 10 kbit/s |
| Medium Range | 1-10 km | Around 10 kHz | 50 kbit/s |
| Short Range | <1 km | > 20 kHz | 100 kbit/s |

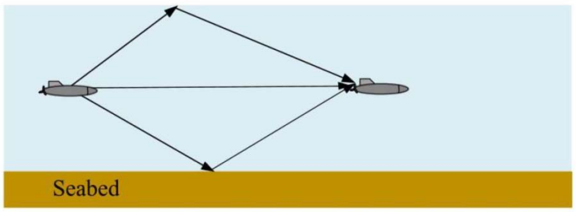



Fig. 8. Multipath effect.

rates in Table V are optimistic and the authors in [15] believe that effective data rates are much lower than those in Table V. Table V indicates the relation between available bandwidth and communication ranges. Additionally, Table V can provide information of a trade-off between formation scale and available bandwidth.

*5) Multipath:* Multipath propagation is illustrated in Fig. 8. When acoustic waves propagate in water, acoustic waves are reflected by sea surface, seabed, or other obstacles. Multipath propagation has multipath effects, which cause distortion in measurement or information accuracy. For acoustic underwater communication, multipath effects are more severe than multipath effects of radio waves in air, especially in some specific scenarios (e.g., in shallow water or ice water). Additionally, since temperature, salinity, and pressure change with water depth, sea regions can be roughly divided by different intervals of propagation speeds. According to Snell's law, acoustic waves bend toward sea regions of intervals of lower propagation speeds [135].

*6) Doppler Effect:* Doppler effect refers to the change in wave frequency if the distance between a transmitter and a receiver increases or decreases. Under the assumption that a relative speed exists between a transmitter and a receiver, Doppler effect or the change in wave frequency can be calculated based on [120], [143].

$$f = f_0\left(1 + \frac{v_r}{c}\right) \tag{2}$$

where $f$ is received frequency, $f_0$ is transmitted frequency, $c$ is a speed of wave propagation, and $v_r$ is a relative speed of a transmitter and a receiver. In equation (2), frequency variation $f_0\frac{v_r}{c}$ is the change in wave frequency or Doppler effect. When $v_r$ is nonzero and $f_0$ is constant, Doppler effect ($f_0\frac{v_r}{c}$) is serious in water since the speed ($c$) of underwater acoustic waves is significant lower than the speed of electro-magnetic waves in air.

For some applications, Doppler effect has several positive impacts: a) a Doppler velocity log is a device that utilizes Doppler effect to calculate speeds of a vessel relative to the seabed [144]; b) Doppler effect can be used to track an underwater target, for instance a submarine in anti-submarine warfare [145]. However, Doppler effect is one of the communication constraints for AUV formation. To compensate or reduce Doppler effect, a number of researchers propose a series of methods. In [146], a dual-pulse technology is used for Doppler estimation and a linear interpolation method is used for high-efficiency Doppler compensation. In [147], a Doppler compensation system is proposed by the authors for high-data-rate acoustic communication. The authors in [147] also claim that Doppler effect can be removed by efficient multi-rate sampling. In [148], the authors assume that a channel has a common Doppler scaling factor on all propagation paths and they propose an approach to reduce Doppler effect by two steps: nonuniform Doppler compensation via resampling and high-resolution uniform compensation of residual Doppler. Since relative speeds of AUVs may be not always constant, the authors in [149] propose a parallel resampling technique to reduce varying Doppler effect.

In summary, above constraints of underwater acoustic communication depend on following aspects, such as depth, temperature, salinity of sea, ocean current, submarine topography, marine organism, communication range, and relative speeds of AUVs. All of above variables cause effects on underwater acoustic communication.

## D. Classification of Network Topologies

Network topologies refer to layout of networks. Network topologies are significant in formation control fields since network topologies define or describe where different AUVs are placed and how these AUVs interconnect with each other. A goal of AUV networks is to exchange information among AUVs so that AUVs can cooperative and achieve formation acquisition, formation maintenance, and formation reconfiguration.

Designing a suitable network topology is essential to achieve formation. In practical situations, for some tasks, AUV formation just needs two or three AUVs to fulfill tasks (e.g., underwater cable inspection). However, for some tasks (e.g., searching a sunken ship), AUV formation needs a large scale. To satisfy different tasks, researchers need to design or adopt various network topologies. In this subsection, we classify the existing papers based on fixed topologies and dynamic topologies, as shown in Table VI. For each kind of topologies, we have separate discussions based on unidirectional information flows and bidirectional information flows. A unidirectional information flow is existed if an AUV obtains information from another AUV but not vice versa, as shown in an example in Fig. 9(a). A bidirectional information flow is existed if two AUV exchange information with each other, as shown in an example in Fig. 9(b). In this paper, we adopt terms of "unidirectional/bidirectional information flows" instead of "unidirectional/bidirectional communications", and we explain the reasons in Section IV-C. We classify topologies into (1) fixed topologies and (2) dynamic topologies as follows.

(1) *Fixed topologies:* A fixed topology means that the topology which defines connection relationships among AUVs does not change with time. Fixed topologies are widely used in

TABLE VI
COMPARISON OF VARIOUS NETWORK TOPOLOGIES

| Network Topologies | | Information Flow | | Control Information | | | | Formation Architectures | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Directional | Unidirectional | Location | Speed | Heading Angle | Pitching Angle | Centralized | Hierarchical | Distributed | |
| Network Topologies | Fixed | • | | | | • | | | • | | [150], [152] [98] |
| | | • | | | • | | | • | | | [151] |
| | | • | | • | | • | | | • | | [153] |
| | | | • | • | | • | • | • | | | [154] |
| | | | • | • | | | | | | • | [57], [156] |
| | | | • | • | • | | | | | • | [155] |
| | Dynamic | • | | • | • | | | | | • | [95] |
| | | | • | • | | | | | | • | [56], [157] |

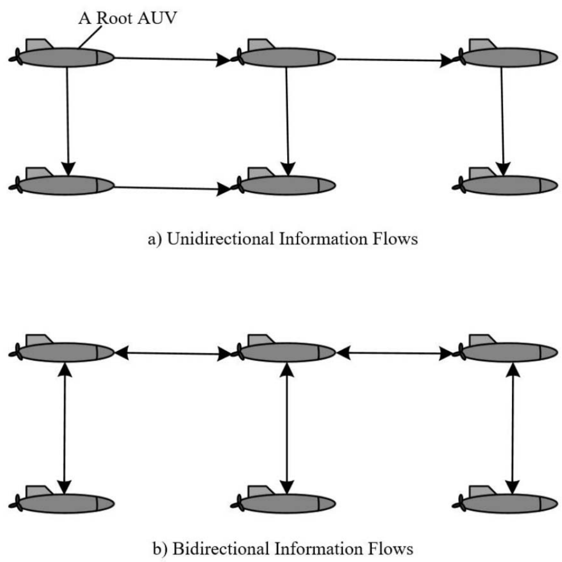



Fig. 9. Information Flows.

both networked control systems and AUV formation control systems. In the literature, there are a number of formation control papers published with fixed topologies in which the authors adopt various control methods, architectures, and assumptions based on different information flows. Next, we discuss the papers based on (a) unidirectional information flows and (b) bidirectional information flows, separately.

(a) *Fixed topologies with unidirectional information flows:* One of the most suitable control methods for unidirectional fixed topologies is tracking control, such as [150], [151], [152], [153], and [98]. Tracking control means that a system with $n$ AUVs can be decomposed into $n-1$ AUV pairs and each pair includes a leader AUV and a follower AUV. If there exists a sequence of leader-follower pairs of the form (AUV $i$, AUV $i+1$), $(\mathrm{AUV}i+1, \mathrm{AUV}i+2), \ldots, (\mathrm{AUV}k, \mathrm{AUV}k+1)$, then AUV $k+1$ is said to be 'reachable' from AUV $i$. A basic assumption of unidirectional information flows is that there must exist at least one root AUV, which can 'reach' every other AUVs, as shown in the example in Fig. 9(a). In each pair, the follower AUV attempts to maintain a desired distance/angle with respect to its leader AUV. Hence, information flows are unidirectional from leaders to followers. If each follower AUV tracks its leader AUV movement, then formation is achieved. The root AUV is significant since the movement states of the root AUV have influences on the whole formation movement. Unidirectional fixed topologies are mostly applied to centralized architectures and hierarchical architectures.

(b) *Fixed topologies with bidirectional information flows:* Control methods of bidirectional fixed topologies are achieved by sharing information among AUVs. Based on AUV relationships of information sharing, bidirectional fixed topologies are mainly used in centralized architectures and distributed architectures. An example of a centralized architecture presented in [154] is explained as follows. A leader AUV is responsible for decision-making and transmitting commands to follower AUVs; the follower AUVs are responsible for executing commands and outputting their own state information to the leader AUV; and the follower states also have influence on decision-making of the leader AUV. Distributed architectures are presented in [57], [155], and [156]. For example, AUVs exchange their state information (e.g., speed/location) with their one or two neighbors; and through negotiating, controllers of each AUV can adjust actuators to achieve that all AUVs have a same speed and keep a desired distance with their neighbors. A basic assumption of bidirectional information flows is that there exists a path between each pair of AUVs. If AUV $i$ exchanges information with AUV $i+1$ and AUV $i-1$ at the same time, a path exists between AUV $i+1$ and AUV $i-1$, as shown in the example in Fig. 9(b).

(2) *Dynamic topologies:* A dynamic topology means the topology which defines connection relationships among AUVs changes with time. In adverse underwater communication environments, maintaining a fixed topology relationship may be difficult. Some researchers attempt to design dynamic topologies with (a) unidirectional information flows or (b) bidirectional information flows.

(a) *Dynamic topologies with unidirectional information flows:* A classic example is presented in [95] with a leader-follower formation strategy with a double-layer topology, including a fixed topology as one layer and a dynamic topology as another. In [95], a leader AUV transmits state information to follower AUVs through a unidirectional fixed topology while follower AUVs exchange speed and location information with each other through a unidirectional dynamic

TABLE VII
COMPARISON OF VARIOUS COMMUNICATION CONSTRAINTS-BASED CONTROL METHODS

| Reference | Communication Constraints | | | | | | |
|---|---|---|---|---|---|---|---|
| | Delay | Noise | Path Loss | Limited Bandwidth | Multipath | Packet Loss | Communication Failure |
| [92] | | | • | • | | | |
| [163] | • | | | | | • | |
| [56] | | | | • | | | • |
| [164] | • | | | | | | |
| [134] | • | • | | | | | • |
| [153] | • | | | | | • | |
| [57] | | | | • | • | | |
| [95] | • | | | | | | • |

topology. To achieve a dynamic topology, a set of several different topologies is predefined in [95]. AUV formation periodically and randomly adopt a topology from the predefined set so that connection relationships among AUVs are time-variant. Each follower AUV obtains leader information and other follower information by the fixed topology and the dynamic topology, respectively. Since each follower AUV makes decisions and arrives coordinations based on both leader's information and other followers' information, the formation architecture in [95] is distributed. In [95], the fixed topology assumes unidirectional information flows, but the dynamic topology doesn't.

(b) *Dynamic topologies with bidirectional information flows:* For dynamic topologies with bidirectional information flows, several studies are proposed. The researchers in [157] point out that fixed topologies are not realistic since the distance between two AUVs could be too long to communicate. The researchers in [157] adopt a distance-dependent dynamic topology. A distance-dependent dynamic topology means that each AUV establishes communication with other AUVs only when they are within its communication range. The researchers in [56] and [134] design random switching topology sets. A random switching topology set includes several predefined topologies and AUV formation periodically and randomly adopts a topology from the random switching topology set. The formation architectures in [56], [134], and [157] are all distributed. Note that the dynamic topologies in [56] and [134] also assume bidirectional information flows.

In summary, most researchers realize that underwater environments are adverse and they propose different methods to build practical network topologies, which contribute a lot in AUV formation fields. However, there are some misconceptions and questionable researches related to communications. We will discuss them in Section IV-C.

## IV. INTERDISCIPLINARY IMPACT ANALYSIS

AUV formation control is an interdisciplinary field involving several aspects including AUV systems, communication, control, etc. Each aspect has impacts on other aspects. In this section, we review and analyze these impacts and interactions. First, in Section IV-A, we discuss formation control with considerations of communication constraints. Second, we discuss and compare mathematical models of AUV dynamics and communication constraints in Section IV-B. Third, in Section IV-C, we identify several common misconceptions and questionable research-directions when researchers try to overcome communication constraints. Finally, in Section IV-D, we survey some underwater network simulators which can potentially used in AUV simulations.

### A. *Formation Control With Considerations of Communication Constraints*

In past twenty years, many papers about AUV formation are proposed [35]. However, most of them ignore communication constraints, such as [98], [158], and [159]. As discussed in Sections II-B and III-C, underwater communication conditions are adverse and communication is one of the significant impacts on formation design.

In this subsection, we summarize the papers about AUV formation with considerations of communication constraints, as shown in Table VII. We survey these papers to understand what are the impacts of communication constraints on formation design and how researchers overcome these constraints.

From Table VII, we can observe that several researchers consider delay in their papers. There exist plenty of proposals about dealing with delay in network-based control systems [160], [161] since delay can cause control system performance degradation or even instability [162]. AUV formation is a kind of network-based control systems with long delays. In [95], [134], [153], [163], and [164], under an important assumption that delays are bounded in AUV formation systems, the authors design formation controllers which can tolerate delays. The authors in [95] assume that time-varying delays have a upper bound and the upper bound is less than the sampling period which is defined as being less than 0.5 seconds in their paper. Sampling periods are time intervals between two instants of sampling control information. The authors in [95] claim that their systems with delays can still achieve stabilization, but take more time to stabilize than the systems without delays. The authors in [153] and [163] consider that packet loss also contributes to an extra delay. The delay upper bounds in [153] and [163] are both related to the maximum propagation delay and the maximum length of packet transmission period. A difference between [153] and [163] is that the authors in [163] adopt packet retransmission techniques. Therefore, the delay upper bound in [163] is also related to the maximum number of retransmission for each packet, whereas the delay upper bound in [153] is also related to the maximum number of consecutive packet dropout. The authors in [153] and [163] define delay upper bound as 0.6 seconds in simulations and prove that their formation systems can still achieve stabilization with $0.6s$ delay. In [134] and [164], the authors consider that a time-varying delay is a continuously differentiable function and the function has an upper bound. Moreover, the authors in [134] and [164] assume that the derivatives of delay functions are always smaller than one. Based on the above assumption, the authors design leader-follower controllers to achieve formation objectives.

The authors in [56], [95], and [134] adopt switching topologies to describe temporary communication failures in their formation networks. Switching topologies are defined as: communication topologies change over time due to temporary communication failures. There exist a series of proposals about network-based systems with switching topologies [165], [166], [167]. The authors in [56], [95], and [134] claim that their formation can still achieve stabilization with switching topologies.

To overcome constraints of limited bandwidth by decreasing amount of control information, the authors in [55], [56], and [57] design formation controllers that only need relative location information since typical formation controllers need at least two kinds of information, such as relative location and speed information. However, since information can be compressed before transmission [168], decreasing amount of control information cannot contribute a lot to deal with bandwidth constraints. We will provide more detail discussions in Section IV-C.

The authors in [57], [92], and [134] consider noises, path loss, and multipath, respectively. We explain these papers as follows.

- The authors in [134] adopt Gaussian white noise to model ocean noises without consideration of AUV-self noises; also, the authors make a leader AUV directly communicate with followers and the followers also can communicate with each other; the formation is stable under the assumption that at least one follower can receive the information of the leader. The assumption is a basic assumption of network topologies in formation control discussed in Section III-D.
- The authors in [92] attempt to optimize power efficiency of AUV formation and consider both path loss and AUV propulsion consumption to find a trade-off between formation scales and energy consumption.
- The authors in [57] consider that multipath can cause information propagation fault for AUV formation. Then the authors in [57] design two fault tolerant consensus controllers to tackle propagation fault. However, the fault model is questionable since the fault model directly modifies the values of signal vectors.
- We will provide more detail discussions in Section IV-C.

In summary, a growing number of researchers realized that communication constrains can disturb AUV formation, as listed in Table VII. Researchers adopt various methods to tolerate or describe communication constraints. However, due to lack of communication background knowledge, some researchers make efforts in unimportant directions. For instance, a) researchers do not need to decrease amount of control information or adopt unidirectional communication to save bandwidth since information can be compressed before transmission; b) since noises and other communication constraints ultimately cause direct effects on physical layers or data link layers, researchers perhaps cannot properly deal with these constraints on formation control. We will provide more detail discussions in Section IV-C.

### *B. Mathematical Models of AUV Dynamics and Communication Constraints*

In order to deeply understand AUV formation with consideration of communication constraints, we survey and analyze the solutions of most typical research papers in the literature. In a control paper, there are two basic parts: defining systems models and designing controllers to provide control inputs for systems. Since AUV formation controllers need to obtain information from neighbor AUVs based on underwater communication, communication constraints can effect controllers. The effectiveness and stability of controllers in a typical reviewed paper are often proved by theories and verified by simulations. In this subsection, we mainly focus on discussing 1) mathematical models and assumptions of AUVs dynamics and 2) mathematical models, model assumptions, and limitations of communication constrains.

Dynamic models are used to express the behaviors of real-world systems over time. Simplified models can help researchers to understand and discuss complex issues. Dynamic models of AUVs can be classified into 2-Dimension models and 3-Dimension models.

*1) A Typical 2-D Model:* A 2-D model of an AUV dynamic can be simplified and described by the following equations:

$$\begin{aligned}\dot{x} &= V\cos\theta + \eta_x,\\ \dot{y} &= V\sin\theta + \eta_y,\\ \dot{\theta} &= W,\end{aligned}$$

where $x$ and $y$ are AUV coordinates in the horizontal plane and $\theta$ is the heading angle with respect to the inertial frame; the control inputs $V$ and $W$ denote linear and angular velocities, respectively; $\eta_x$ and $\eta_y$ are unknown disturbances; and finally all these variables are functions of time.

Based on the above 2-D model of AUVs, the authors in [153] attempt to control AUV formation under propagation delays and packet drops explained as follows. 1) The leader AUVs periodically send packets of state information to their followers; 2) once a packet is successfully received by receiver AUVs, the receiver AUVs update their states of controllers; 3) there are explicit assumptions as follows: a) all AUVs transmit packets with a constant period $h$; b) the propagation delay $l$ is positive and bounded; and c) $n$, the number of consecutive packet drops, is positive and bounded; 4) a total delay

TABLE VIII
6 DEGREES OF FREEDOM

| 6 Degrees of Freedom | Definitions | Positions and Attitude Angles | Linear and Angle Velocities |
|---|---|---|---|
| Surge | Moving forward or backward on x-axis | $x$ | $v_x$ |
| Sway | Moving left or right on y-axis | $y$ | $v_y$ |
| Heave | Moving up or down on z-axis | $z$ | $v_z$ |
| Roll | Tilting side to side around x-axis | $\phi$ | $p$ |
| Pitch | Tilting forward or backward around y-axis | $\psi$ | $q$ |
| Yaw | Turning left or right around z-axis | $\gamma$ | $r$ |

$\lambda$ is defined as the time difference between the current time and the instant in which the last packet received by the follower was sent; 5) the effects of propagation delays and packet drops are grouped into the total delay $\lambda$ so that the total delay is presented as $\lambda = (1+n)h+l$; 6) Since *n* and *l* are bounded, there exist a maximum total delay $\lambda_m = (1+n_{max})h + l_{max}$ and the total delay is described as: $0 \leq \lambda \leq \lambda_m$; 7) then the authors design formation controllers using an approximation of a average delay, i.e., $\lambda = \lambda_m/2$.

There are several limitations of the above delay model in [153]. First, the model does not consider a packet retransmission mechanism since $\lambda$ does not contain the parts of retransmission delays. Second, since the rate of packet loss in underwater can reach 20%-50% [126], *n* could be unrealistic large so that the value of *n* may be not upper bounded by a reasonable value. Third, the average delay is not accurate at all. Finally, due to the above reasons, the maximum value of $\lambda$ may not exist at all so that the designed controllers could encounter failures when communication channels are bad.

*2) 3-D Models:* Movements of AUVs in 3-D environments can be described by 6 degrees of freedom (6-DoF) including Surge, Sway, Heave, Roll, Pitch, and Yaw, shown in Table VIII. AUV 6-DoF can be divided into translation motion and rotation motion. We list the notations of AUV 6-DoF in the Table VIII. To provide a clear view, we describe the physical meanings of 3-D dynamic equation parameters in Table IX and will not provide additional explanation to the parameters used in the next.

Body-fixed reference frames and the global coordinate frame are useful to describe 6-DoF of AUV movements. Origins and axes of body-fixed reference frames remain fixed relative to AUVs. Origins and axes of the global coordinate frame remain fixed relative to the Earth. Based on above two frames, the authors in [169] and [170] design a well-known model of an AUV dynamic:

$$\dot{p} = J(p)v,$$
$$M\dot{v} + C(v)v + D(v)v + g(p) = \tau + \Delta, \quad (3)$$

where $\Delta$ denotes unknown disturbance.

TABLE IX
NOTATIONS IN AUV DYNAMIC EQUATIONS

| | |
|---|---|
| $p_1 = [x, y, z]^T$ | AUV positions |
| $p_2 = [\phi, \psi, \gamma]^T$ | AUV attitude angles |
| $p = [x, y, z, \phi, \psi, \gamma]^T$ | Positions and attitude angles |
| $v_1 = [v_x, v_y, v_z]^T$ | Linear velocities of AUVs |
| $v_2 = [p, q, r]^T$ | Angle velocities of AUVs |
| $v = [v_x, v_y, v_z, p, q, r]^T$ | Linear velocities and angle velocities |
| $\tau_1$, $\tau_2$, and $\tau$ | Control input |
| $J_1$, $J_2$, and $J$ | Transformation matrices from the body-fixed reference frame to the global coordinate frame |
| $M_1$, $M_2$, and $M$ | Inertia matrices |
| $C_1$, $C_2$, and $C$ | Coriolis and centripetal matrices |
| $D_1$, $D_2$, and $D$ | Hydrodynamic damping matrices |
| $g_1$, $g_2$, and $g$ | The force generated by the difference between the center of gravity and the center of buoyancy |
| $\Delta$ | Unknown disturbance |
| $F_x$ | Total force along $X$ axis |
| $F_y$ | Total force along $Y$ axis |
| $m_x$ | AUV mass and attached mass along $X$ axis |
| $m_y$ | AUV mass and attached mass along $Y$ axis |
| $I$ | Moment of inertia around $Z$ axis |
| $\Omega$ | Total moment around $Z$ axis |

The above 3-D models are difficult to design controllers. Therefore, researchers usually simplify above models by utilizing several assumptions in order to design controllers. Next, we provide a comparison of the AUV models in the reviewed papers described in the Section IV-A.

The authors in [95], [134], and [164] have three assumptions about AUV dynamics; 1) roll angles and velocities of AUVs can be ignored; 2) AUV shapes are symmetrical in horizontal and vertical planes; 3) the center of gravity and the center of buoyancy are coincident so that *g*(*p*) is zero. Based on above assumptions, the authors can simplify the equation (3) into a standard second-order model:

$$\dot{p} = v,$$
$$\dot{v} = \tau.$$

In [95], [134], and [164], the authors all consider time-varying delays in AUV communications.

In [95], the time delay is defined as $\lambda < T < 0.5$, where *T* is the sampling period of systems. To describe the limitation, we need to describe the controller structure of the *i*-th AUV in [95] as follows:

$$\tau_i = \beta_1\{A(p_i - p_{i+1}) + B(p_i - p_l)\} + \beta_2\{C(v_i - v_{i+1}) + D(v_i - v_l)\}, \quad (4)$$

where $\beta_1$, $\beta_2$, *A*, *B*, *C*, and *D* are parameters in the controller; $p_i$ and $v_i$ are position state and velocity state of *i*-th AUV, respectively; $p_{i+1}$ and $v_{i+1}$ are position state and velocity state of a neighbor of *i*-th AUV, respectively; $p_l$ and $v_l$ are position state and velocity state of the leader AUV, respectively. The first and third terms are used to keep formation with the AUV neighbor. The second and forth terms are used to keep formation with the leader AUV.

In the situations without delays, the $\beta_1$ and $\beta_2$ are constant parameters. In the situations with delays, the $\beta_1$ and $\beta_2$ are defined as functions related to $\lambda$. The parameters of controllers are predefined and an implicit assumption in [95] is that the $\lambda$ is known in advance when designing controllers. However, a known delay is a very strong assumption which often cannot be satisfied in real systems.

In [134] and [164], the time-varying delay $\lambda$ is a continuously differentiable function. The papers assume that $\lambda$ is always positive, $\lambda$ has an upper bound, and $\dot{\lambda}$ is always less than 1. The main limitation of delay models in [134] and [164] is that their delay models are idealized. Due to the non-negligible rate of packet drops, the function $\lambda$ in [134] and [164] maybe neither continuous nor differentiable.

Moreover, the authors in [134] consider that ocean noise can disturb communication. The controller structure in [134] is the same as the equations (4). The authors in [134] consider that if the communication is disturbed by noise, the parameters *A*, *B*, *C*, or *D* in equation (4) are equal to 0; otherwise *A*, *B*, *C*, or *D* are equal to 1. The noise model in [134] has major limitations. First, in most of situations, noise in underwater always exists so that the above parameters are always zero and then the controller does not known the state information of other AUVs. Second, if the communication signals are disturbed by noise, an AUV may not receive the information from other AUVs, but still can obtain itself information. The parameters *A*, *B*, *C*, or $D = 0$ represent that the controller does not known both the state information of other AUVs and the state of the AUV itself.

The authors in [56] and [57] assume that all AUVs in formation have fixed attitude angles. Therefore, AUVs only have 3 DoF and the equation (3) can be rewritten as:

$$\begin{aligned}&\dot{p}_1 = J(p_2)v_1,\\&M\dot{v} + D(v)v + g(p) = \tau.\end{aligned}$$

In [56] and [57], the authors consider limited bandwidth of underwater acoustic communication and design AUV formation in which AUVs only transmit their position information to other AUVs. The *i*-th AUV controller can be updated based on itself velocities $v_i$, itself positions $p_{1i}$, and position information $p_{1(i+1)}$ of a neighbor AUV.Moreover, the authors in [57] consider that multipath effect can affect communication. The original communication signals are $[p_{1i} - p_{1(i+1)}]$. Under multipath effect, the communication signals are presented as $A(t)[p_{1i} - p_{1(i+1)}]$, where *A*(*t*) is a unknown time-varying fault function. The assumptions of *A*(*t*) is that: a) *A*(*t*) has certain lower and upper bounds; b) the lower and upper bounds are not equal to 1 at the same time. The main limitation the model of multipath effect in [57] is that the multipath effect can affect communication and cause signals delay or loss, but is not likely to directly change the signal values as modeled.

The authors in [163] assume that the shapes of AUVs can be approximated as sphere shapes. Thus, AUVs have three planes of symmetry and the *M* and *D*(*v*) in the equation (3) are diagonal matrices. The equation (3) is rewritten as:

$$\begin{aligned}&\dot{p}_1 = J_1(p_2)v_1,\\&\dot{p}_2 = J_2(p_2)v_2,\\&M_1\dot{v}_1 + C_1(v_1)v_2 + D_1(v_1)v_1 + g_1(p_2) = \tau_1,\\&M_2\dot{v}_2 + C_1(v_1)v_1 + D_2(v_2)v_2 + g_2(p_2) = \tau_2.\end{aligned}$$

Similar to [153], the authors in [163] attempt to control AUV formation under delay and packet drops. The effects of propagation delays and packet drops are grouped into a total delay $\lambda$. Moreover, the authors in [163] consider that retransmission techniques are adopted in AUV formation. Therefore, in [163], the total delay is described as $\lambda = (1+n)h + k + t_r\frac{a}{1-a}$, where $t_r$ is retransmission time and *a* is the rate of packet loss. Although the model of the total delay in [163] is more practical than the model in [153] by considering retransmission, it has several limitation as follows. First, the retransmission delay model is not accurate since the rate of packet loss is an average value and the variance could be big. Second, the value of *n* may be not upper bounded by a reasonable value. Finally, due to the above reasons, the total average delay can be a big difference from the actual delay so that the designed controllers could encounter failures when the situations are not expected.

The AUV dynamic is coupled, where coupling means that different state variables are interacted. The authors in [92] assumes that dynamic systems of AUVs can be separated into three non-interacting (or lightly interacting) systems and the dynamic equations can be separated into three sets of equations. Moreover, the authors assume that roll, pitch, and heave can be ignored in the application of the paper [92]. Therefore, the movements of AUVs only have 3-DoF. The dynamic equations are rewritten as follows:

$$\begin{cases}\dot{x} = v_x\\ m_x\dot{v}_x = F_x\end{cases},\quad \begin{cases}\dot{y} = v_y\\ m_y\dot{v}_y = F_y\end{cases},\quad \begin{cases}\dot{\gamma} = r\\ I\dot{r} = \Omega.\end{cases}$$

The authors in [92] design AUV formation with high coverage efficiency and small communication power consumption since the above two objectives are both related to the distances among AUVs.The authors consider that path loss can cause communication signal energy attenuate and adopt the equation (1) listed in the Section III-C to estimate the attenuation factor. The equation (1) can obtain attenuation factor and communication power consumption is related with the attenuation factor. However, coverage efficiency and communication power consumption have many factors besides attenuation of path loss. When distances among AUVs change, many factors can affect communication power consumption. For example, a) when distances among AUVs decrease, AUV propellers' noise or Doppler effect can increase the rate of packet drops and retransmissions of lost packets consume extra energy; b) Based on various communication protocols, back-off time or probabilities of frame collision also affect communication power consumption when distances among AUVs change.

*3) Summary:* In summary, although the above reviewed papers have various limitations, the researchers make an important contribution to the subject of AUV formation since

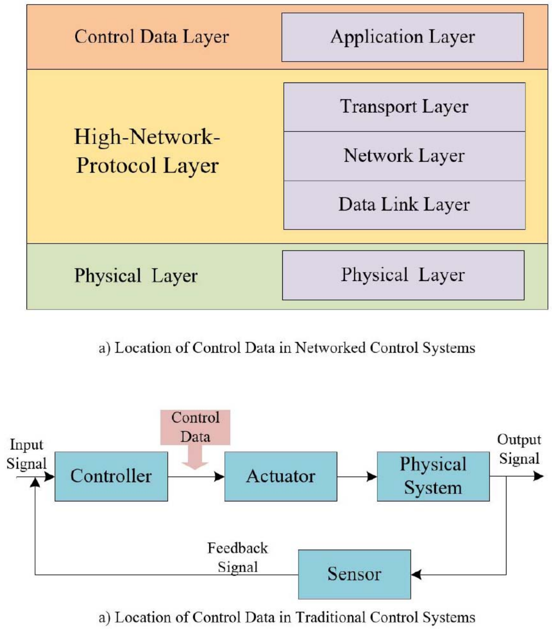



Fig. 10. Locations of Control Data

most papers of AUV formation do not consider communication problems. Due to lack of knowledge of underwater acoustic communication, the researchers cannot define a rational model of communication constraints. Without rational models, researchers are difficult to deal with AUV formation under communication problems. Moreover, we identify several misconceptions and questionable researches of the reviewed papers in next subsection.

### C. Misconceptions and Questionable Researches in Formation Control

When we classify the network topologies of AUV formation and survey the AUV formation papers with consideration of communication constraints, we realize that several researchers consider both communication problems and control problems of AUV formation at the same time. However, due to interdisciplinary features of AUV formation, researchers have several common inaccurate concepts or misconceptions and even work toward to questionable researches. In this subsection, we identify some inaccurate concepts or misconceptions and questionable researches as follows.

(1) *Unidirectional/bidirectional communication:* In most of formation control papers, the authors use the terms of “unidirectional communication” and “bidirectional communication”. However, we believe that the terms are both inaccurate and misleading with reasons as follows. We consider AUVs which adopt commercial communication mechanisms which implement the communication protocol stack as shown in Fig. 10(a) instead of raw communication (e.g., bus communication) as shown in Fig. 10(b). While traditional, typical control systems follow Fig. 10(b) in which control data are transmitted via the physical layer directly, most of networked control systems follow Fig. 10(a) in which control data in fact belong to the application layer in the networking protocol stack. We believe that AUVs more likely adopt commercial communication mechanisms to form networked control systems instead of raw communication. Therefore, we can abstract AUV communication in three layers: the physical communication layer, the high-network-protocol layer, and the control data layer (i.e., the application layer), as shown in Fig. 10(a). Our studies show that what formation control authors called “unidirectional communication” and “bidirectional communication” are in fact are the control data (application) layer instead of physical-layer communications or network-protocol-layer communications. The control data layer (i.e., the application layer) is independent of the physical communication layer and the high-network-protocol layer. It is highly possible that data in the control data layer is “unidirectional” while the physical communication layer adopts “bidirectional”. Therefore, we adopt terms “unidirectional/bidirectional information flows” instead of “unidirectional/bidirectional communications” in this paper. We believe that many control researchers confuse control data communication with physical layer communication, particulary in networked control systems. The former is in the application layer and the latter is in the physical layer if commercial communication mechanisms are adopted instead of raw communication (e.g., bus communication).

(2) *Delay-bounded Formation Control:* As we stated in the last subsection, researchers design formation controllers under the assumption that the communication delay is bounded and small [95], [153], [163].However, we believe that it is an unrealistic assumption as explained as follows. First, as stated in the above, the control data is in the application layer so that it is difficult to estimate delays caused by lower network protocol layers, particulary with AUV mobility under unknown underwater environments; second, we cannot assume that delays are small so that the control systems can handle the delays since very long prorogation delays in underwater are well known; we believe that long delays are more likely beyond the tolerance of the control systems; therefore, we believe that there is not a small delay bound due to the above reasons. It is dangerous for AUV formation control to assume such a bound since if the real delay is larger than the bound, the formation control will fail.

(3) *Formation Control with packet retransmission techniques, noises, path loss, multipath, etc.:* Of course, cross-layer designs are possible and have many examples [171]. However, many of the formation control papers have bad cross-layer designs among the control data layer and the lower network/communication layers. For example, the authors in [163] adopt packet retransmission techniques to determine the delay in formation control. The authors in [57], [92], and [134] consider noises, path loss, and multipath, respectively. Calculations of path loss can be used to find a trade off between formation scales and communication power consumption [92], whereas communication power consumption is related to many factors, such as communication protocols, modem abilities, etc. We believe that multipath and noises may not have direct effects on designing formation since AUV formation can be regarded as application layers in networks. Multipath and noises have direct effects on physical layers or data link layers and these effects ultimately cause varying

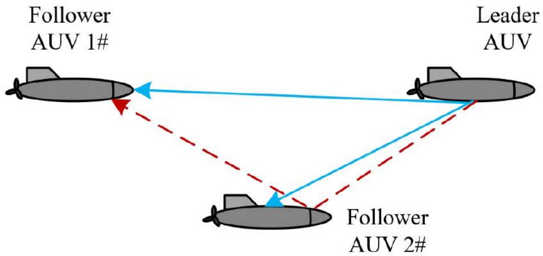



Fig. 11. An Example of the Difference Between Information Flow Direction and Communication Direction

delays on AUV formation. Moreover, under an assumption that communication would not permanently fail, all communication constraints listed in Section III-C ultimately cause varying delays on AUV formation.

(4) *Bandwidth saving using unidirectional communication:* Some authors claim that they adopt unidirectional communication because unidirectional communication needs less bandwidth than bidirectional communication. However, based on our above discussions, control data belong to the application layer as shown in Fig. 10(a) and data traffics (called information flows in this paper) in the application layer are not directly related to bandwidth in the physical layer.

- If we assume that unidirectional data do save traffic, they only save control data traffic in the application layer, but neither bandwidth the network layer (i.e., throughput in computer science terminology) nor bandwidth the physical layer (in electrical engineering terminology).
- Unidirectional information flows cannot guarantee less traffic in lower layers due to the information hiding of lower layer protocols to the application layer. In other words, the application layer has no clue how the lower layers do the job, e.g., if the physical layer retransmits multiple times or not and if routing overhead of one approach in the network layer is less than another approach in the network layer or not. Fig. 11 illustrates an example of the difference between the information flow direction and the communication direction as follows.
  - blue arrows represent the information flows' directions between the leader AUV and follower AUVs;
  - red arrows represent communication directions among AUVs;
  - in the control relation, the leader AUV directly gives commands to two follower AUVs so that the information flows are from the leader AUV to follower AUVs;
  - however, in the communication relation, follower AUV #2 can work as a relay node and forwards communication packets to follower AUV #1 in the network layer (i.e., routing);
  - in such an example, we cannot guarantee that unidirectional means less traffic in the lower layers.
- Bidirectional information flows have the advantage that they provide robust and reliable formation, explained as follows.
  - In bidirectional information flows, a leader AUV has a better idea of other AUVs' locations and availability. On the other hand, a leader AUV with unidirectional information flows cannot even know whether follower AUVs arrive desire locations or not.
  - Since wireless communication has high rates of packet loss or transmission errors in underwater environments [172], acknowledgements from receivers are necessary for transmitters to determine whether retransmissions of packets are needed.

(5) *Traffic Saving using different topologies for different control data:* To reduce the amount of communication information, the researchers in [95] and [134] design a double-layer topology. The double-layer topology includes a speed topology and a location topology so that AUVs can transmit speed information and location information independently. However, we believe that independently transmitting speed and location information will have more overhead/traffic and cannot save traffic at all. First, double-layer topologies will have at least double numbers of data packets; second, separating a matrix (both speed and location information) into two vectors (independent speed and location information) cannot decrease the number of packets at all since they are all included in data packets; the payload with a couple of bytes longer does not provide much more overhead, but two separate packets provide much high overhead in the lower layer proctors; this is the reason that in many of networking researches, we adopt aggregation of small packets instead of sending them separately to save traffic [173], [174]; third, more data packets can increase data collisions and communication burdens.

(6) *Saving half of the traffic by saving half of the information:* As we stated in the previous subsection, some authors limit bandwidth by decreasing amount of control information [55], [56], [57] via sending relative location information instead two kinds of information: relative location and speed information. However, we believe that this is a misconception. First, control data need to be put into packets while packet sizes often cannot be too small. For example, in Ethernet, there is a minimum packet size requirement. Second, sending two kinds of information appears to double the information, but this only increases very little in term of the sizes of the packets. Let $H$, $P$, and $P+Q$ denote the header overhead, the control information, and the increased control information, respectively, assuming that the control information increases from $P$ to $P+Q$ in length. When the control information increases from $P$ to $P+Q$, the increased percentage $r$ in the packet is defined as follows:

$$r = \frac{P+Q-P}{H+P} = \frac{Q}{H+P}. \tag{5}$$

Since the control information (either $P$ or $P+Q$) is normally small and the packet header overhead ($H$) is large, the ratio $r$ will be small. Let's give an example as follows. Assume that each control information is 16 bits, i.e., $P=2$ bytes and two control information is $P+Q=4$ bytes in length. Assume that packets are transmitted in WiFi over IP which is over TCP socket and WiFi uses IEEE 802.11a. The physical layer header overhead is at least 44 bits (i.e., 6 bytes) [175], the medium access control (MAC) header is

40 byes, the IP packet header is at least 20 bytes, and the TCP segment header is at least 20 bytes so that the header overhead is $H = 6 + 20 + 20 + 40 = 86$ bytes. If we have one control information (i.e., $P = 2$ bytes), the overhead is $H/(H + P) = 97.7\%$. Now, if assume that we use two control information (i.e., $P + Q = 4$ bytes) instead of one control information, the packet length increases from $H + P = 88$ byes to $H + P + Q = 90$ bytes, which is only $r = (P + Q - P)/(H + P) = 2.3\%$ increase in terms of percentage. In other words, doubling the control information just increases a tiny bit in the packet size. Note that we use WiFi as an example instead of acoustic communication, but the result will be similar. In summary, if the control information is small, saving control information almost is not effective to save traffic at all.

### D. Underwater Mobile Network Simulators

As the above discussions, AUV networks are affected by various aspects. To verify the validity of the underwater network protocols, directly testing the protocols in real underwater environments is the most reliable proof method [176]. However, real-life experiments bring high costs of both time and money. Over the past decade, several underwater network simulators are developed and widely used in various research projects [177], [178], [179], [180]. We introduce three mature simulators as follows.

World Ocean Simulation System (WOSS) is a nice simulation tool and tested on three protocols: ALOHA, Tone-Lohi, and Distance-Aware Collision Avoidance Protocol [181]. The significant features of WOSS include a) providing a reliable simulation accuracy via integrating with Bellhop which can provide real oceanographic parameters so that WOSS achieves a realistic reproduction of acoustic propagation and b) integrating with oceanographic parameters of users to improve simulation accuracy of a specific network situation. The features of WOSS can make users conveniently evaluate the performance of the underwater protocols before executing real-world experiments [182].

Design, Simulate, Emulate and Realize Test-beds for Underwater network protocols (DESERT) is a public C/C++ library set for helping designing and implementing underwater network protocols [183], [184]. DESERT provides a series of modules for all layers of protocol stacks defined by TCP/IP protocol standards. Additionally, DESERT has four different mobility modules to simulate underwater robot movements [182]. The most remarkable feature is that DESERT can interface with real modems. The feature allows users to use the same code when they evaluate their networks in both simulations and real-world experiments.

Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET) is a tool to test and implement protocols of underwater networks [185]. SUNSET can validate and evaluate various network configurations (mobile/static nodes in single-hop/multi-hop networks) at sea, rivers, or lakes. Similar to DESERT, SUNSET also can reuse the same code for simulations and real-world experiments. A feature of SUNSET is that SUNSET has several core modules besides modules of protocol stack layers, such as utility module, timing module, debug module, statistics module, and information dispatcher module. The core modules can provide useful functions to improve SUNSET performance. For example, timing module can compute the delays in real devices, which are usually ignored when designing in simulations.

The three above simulators are all open source and based on the Network Simulator version 2 (ns2) and NS-MIRACLE simulation softwares, where the NS-MIRACLE is the extension of ns2. The same simulation engines provide high compatibility and interoperability among the three simulator systems when they work on simulation modes [186]. For emulation modes, DESERT and SUNSET both have adopt different methods to run emulation modes. The main difference between DESERT and SUNSET can be summarized as two aspects: a) DESERT uses the real-time scheduler of ns2 and SUNSET has its own real-time scheduler; b) they adopt different mechanisms to convert ns2 packets into byte streams. The authors in [187] believe that when work on the emulation mode, DESERT is simple to implement but lack of efficiency, whereas SUNSET is a little complex to implement but can provide higher scheduling accuracy and a higher efficiency than DESERT.

All of above simulators are not designed for AUV formation control which needs more than underwater communication protocols. We will discuss this more in Section V for future research directions.

## V. Future Research Directions

AUV formation is an interdisciplinary of AUV features, formation control, and communication. There exists a crucial gap between theoretical research and practical situations. We summarize three reasons about why the development of AUV formation is still in an early stage: a) some researchers make efforts in unimportant directions as mentioned in Section IV-A; b) some researchers propose or adopt several methods to describe or overcome communication constraints in theoretical research, but there lacks verification of these methods in practical experiments; c) some theoretical studies are under strong assumptions and the assumptions are difficult to achieve in practical, such as mentioned in Sections III-D and IV-C. Based on the purposes of designing practical AUV formation, we propose several future research directions.

- In our opinions, designing delay-tolerated AUV formation systems is a research direction since delays inevitably exist in all network-based control systems. Moreover, we list two open issues about delay-tolerated AUV formation as follows.
  - First, we need to find a method to calculate values of delay upper bounds for AUV formation systems. Although different variables related to values of delay upper bounds are given in [95], [153], and [163], the authors of these papers do not explicitly explain how they obtain values of delay upper bounds. We notice that many researchers contribute to how to calculate the delay upper bounds of

delayed systems [188], [189], [190], [191]. We also need to find a method to calculate values of delay upper bounds for AUV formation systems.
  - Second, if we can calculate values of delay upper bounds that AUV formation systems can tolerate, we also need to estimate how large the delay ultimately affect AUV formation in practice. Delays on AUV formation are related to many factors, including communication protocols, communication conditions, distances among AUVs, etc. Building function models to calculate delays on AUV formation is difficult. Perhaps we need to directly obtain delay values based on experiments in underwater.
- A series of researchers adopt switching topologies to describe temporary communication failures in their formation networks. There exist several interesting research directions about how to deal with communication failures.
  - First, if one or more AUVs permanently fail rather than 'temporary communication failures', does there exist a suitable network topology to describe this situation? In practical situations, AUVs may permanently fail due to some reasons, such as AUV broken or collision, marine organism attacks, ocean current disturbance. We need to build suitable network topologies to describe the formation systems in which one or more AUVs permanently fail.
  - Second, we need to build AUV formation which can tolerate a part of AUV failures. Delay-tolerated AUV formation systems are built under an assumption that communication would not permanently fail. In practical situations, we cannot ensure that above assumption is always valid since there exist many uncertain factors in underwater environments.
- An important future research direction is to comprehensively study assumptions related to communications made in control or formation control to see the practical and realistic implication and their impacts. After this comprehensive study, more realistic formation control methods can be designed considering all three aspects of AUV performance, formation control, and underwater communication capability in a practical and realistic way.
- Nearly all of formation control papers are developed under some assumptions. Some assumptions are not significant challenges for vehicles in air or on ground. However, in underwater environments, it is not easy to guarantee that the assumptions are always available, especially, some AUVs (e.g., gliders) need to work for several months. The most likely scenario is that unpredictable disturbances separate the whole AUV teams into several parts. One research direction is to design robust recovery mechanisms when formation control fails.
- Although there are some existing underwater network simulators, all of the simulators focus on underwater communication/network protocols, but not AUV formation control. Therefore, another future research direction is to implement AUV formation control into underwater mobile network simulators, such as DESERT Underwater (http://desert-underwater.dei.unipd.it), which has features such as interference, multipath, vessel noise, mobility, etc., to study impacts of underwater communications on AUV formation control. In order to simulate AUV formation control, we need to consider AUV performance, applications, communication, and control strategies. All of above factors together affect the AUV formation. For example, various communication protocols can cause various delays and energy consumption since protocols have different methods to deal with packet loss or other communication problems. However, the time-delay threshold that AUV formation can tolerate is determined by the control strategies. If AUV formation with certain protocols attempts to keep time-delay under a threshold, AUVs may need to decrease communication distance. Decreasing distance among AUVs further influences applications of AUV formation.
- The effects of communication constraints on the controller need to be modeled mathematically. A practical mathematic model can greatly promote the development of AUV formation. To date, the researchers in control disciplines design mathematic models of communication constraints with a series of strong assumptions due to the lack of communication knowledge.

In summary, we believe that a practical AUV formation system needs to both tolerate delays and a part of AUV failures. To achieve practical AUV formation, researchers need to consider communication, formation control, and AUV features together.

## VI. Conclusion

In this paper, we introduce AUV performance and formation control as a background. We propose a classification framework with three dimensions based on AUV performance, formation control, and communication capability. We summarize various AUV subsystems, such as navigation systems, communication systems, energy systems, and functional sensor systems. Additionally, we collect a series of up-to-date modem products from different manufacturers to offer an overview about features of acoustic modems. We categorize AUVs into biomimetic AUVs, underwater gliders, and torpedo shape AUVs based on their body shapes. Based on significant features of different shape AUVs, we conclude: a) to satisfy various tasks, torpedo shape AUVs have balance performance and can be built very large with various equipment; b) although underwater gliders have relative slow speeds, their extremely high endurance guarantees that they can travel thousands of kilometers in a single deployment; c) biomimetic AUVs are lightweight and can move fast as well as torpedo shape AUVs, but most of them work at nearly shallow water; d) the light weight of gliders and biomimetic AUVs is cost-effective since they can be launched from small vessel by only one or two people, inducing deployment costs. We list a series of underwater communication constraints. Moreover, we observe that communication constraints depend on following aspects, such as depth, temperature, salinity of sea, ocean current, submarine topography, marine organism, communication range, and relative speeds of AUVs. All of above variables cause effects on underwater acoustic communication. We summarize and classify network topologies of AUV formation based on fixed topologies and dynamic topologies with unidirectional or bidirectional information flows. We identify some common misconceptions and questionable research for formation control related to communication. For examples, we point out that assuming a small bound delay is unrealistic and dangerous for underwater AUV formation control; reducing control information in half does not reduces the traffic in half at all and in fact it only decreases traffic in a tiny bit due to both the small length of control information and the larger overhead of headers of network protocols.

Furthermore, we study existing AUV formation papers with considerations of communication constraints to learn which communication constraints they consider and how they overcome them. Based on surveying AUV formation, we notice that there exists a crucial gap between theoretical research and practical situations in AUV formation fields. We analyze why the development of AUV formation is still in an early stage and point out several research directions.

AUV formation has valuable application prospects. To the best of our knowledge, it is the first time in the literature to present an integrated survey on AUV formation. We hope that our survey can offer useful information for researchers who are interested in AUV formation.

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