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Low-cost Underwater Swarm Acoustic Localization: A Review

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ABSTRACT Underwater swarm robotics has gained prominence as an innovative paradigm for diverse applications, including environmental monitoring and marine exploration. This review paper presents a comprehensive review of low-cost underwater swarm acoustic localization systems, focusing on recent research findings validated through field experiments. To aid research on the concept of low-cost swarm acoustic localization, this article provides overview of cost-effective underwater swarm applications and the applicability assessment of traditional acoustic localization strategies, then presents several crucial components for building an acoustic ranging-based low-cost swarm localization system, including low-cost acoustic modems and low-cost swarm localization system with cooperative strategies. In summary, this review serves as a valuable resource for researchers and practitioners in underwater swarm robotics and acoustic localization, addressing challenges, strategies, and goals of low-cost swarm acoustic localization systems.

INDEX TERMS Acoustic localization, acoustic modem, low-cost underwater localization, UUV Swarm.

I. INTRODUCTION

SWARMS of Unmanned Underwater Vehicles (UUVs) have been substantially used for marine offshore missions and deep ocean exploration. Compared to a single underwater vehicle, underwater vehicle swarms address the shortcomings of limited energy budget and coverage of area, insufficient sensing capabilities, while offering reduced operation time required and collaborative decision-making abilities. A wide variety of marine applications can be achieved using a swarm of UUVs, from military ones like border monitoring and control, underwater reconnaissance and surveillance [1], to scientific ones such as data muling [2], water quality and aquatic lifeforms studying, seismic and tsunami monitoring [3], tectonic plate movement investigation, deep sea exploration [4], oceanographic surveys, bathymetric data collection [5], and industrial applications like oil and gas reservoir exploration, extraction of natural resources, and underwater pipeline monitoring [6], [7]. With smaller and cheaper UUVs developed in the past decade, the utilization of swarms of UUVs has become an emerging topic in underwater research. According to a bibliometric analysis of current scientific literature, the publications related to UUVs deployed for marine environmental monitoring tasks have increased exponentially in recent years [8]. For example, chemical pollutants like microplastics are the emerging concern for the coastal water ecosystems and challenges still remain in assessment of the pollution and monitoring techniques [9]. The recent development of the robot field has made UUVs the cost-effective alternative compared to the traditional research vessels which have high resource management cost and long preparation effort [8]. Moreover, UUVs are the safe choice for pollution monitoring since they can collect samples in hazardous areas without human exposure compared to the conventional inspection process with divers [10]. Various low-cost UUVs have been developed, such as underwater buoyancy gliders for monitoring in littoral zones, drifting sensor packages for long term coordinated monitoring and Autonomous Underwater Vehicles (AUVs) for detection of soniferous animals [11]. As a result, fleets of UUVs with sensing techniques can be deployed with moderate cost and effort, while providing major benefits of long mission duration, larger area coverage and reduced effort of single vehicle [11]. In **Fig. 1** popular marine applications using underwater swarm UUVs are presented.

Localization is one of the most critical problems for underwater robotic swarms. Due to the rapid attenuation of electromagnetic (EM) signals in water, high frequency signals propagate only short distances, which is the reason why

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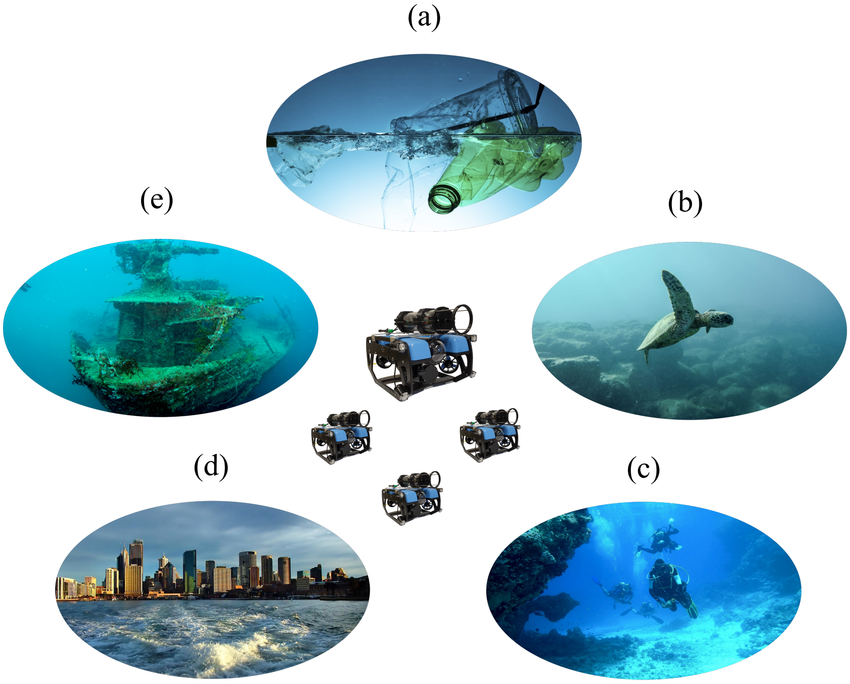

FIGURE 1. Representation of marine applications using UUV swarms: (a) Water pollution monitoring, (b) Aquatic lifeform monitoring, (c) Divers' network, (d) Tsunami monitoring system, (e) Deep sea shipwreck inspection. Middle: representation of UUV swarm (BlueROV2 [12]).

Global Navigation Satellite System (GNSS) is unfeasible underwater [13]. Techniques for underwater vehicles localization include acoustic, optical, dead-reckoning, geophysical and sensor fusion [14]–[17]. Acoustic communication has been the canonical technique for underwater localization due to the long range communication capability it provides. However, due to the restricted channel conditions, acoustic communication is also subject to long propagation delay, high power consumption, low bandwidth, scattering, multipath interference and Doppler shift, etc [13]. Moreover, for a collaborative team of UUVs, it is crucial that the vehicles can communicate and share information with each other. However, there are still limited studies for reliable communication and networking among the UUVs, or between the UUVs and the control center. These factors all have posed challenges for underwater swarm localization solutions to achieve the desired properties such as, high accuracy, fast convergence, wide coverage, good scalability, as well as low cost of deployment and communication [18].

With the maturity of physical layer technology and emergence of low-cost underwater vehicles as well as cheap communication modems in the last decade [14], one can envisage that swarm applications to be widely used in civil applications and underwater research in the near future. For the localization problem in these swarm applications, one also has to take into consideration a critical component, the cost. Depending on the budget, the choice of UUVs, the sensor suite and accordingly the localization strategies will vary. Here we define several aspects that have to be counted in a low-cost underwater localization system: First, the swarm vehicle should have a low-cost-per-unit design which is easy to manufacture, reliable and highly-maneuverable; Second, the vehicle should also be easily portable (e.g. size $<2\,\mathrm{m}$), with low deployment and retrieval effort, equipped with low-cost systems for communication, navigation and perception; Third, the localization method should be energy efficient and requires low communication traffic among agents in the swarm; Fourth, platforms and testbeds for the evaluation and testing of the localization solutions should also be easily accessible and low-cost. Despite lower cost is favorable for civil and research applications, the trade-off between the cost and the localization accuracy has to be considered and catered for in individual applications. For example, with low-cost vehicles and limited sensor and battery budget, swarm localization systems could be deployed in various underwater applications in shallow water environments such as lakes, lagoons, harbors and ports, while highly-customized requirements of depth rating, communication range, operation time, sensing resolution and localization accuracy need to be met.

The main contribution of this article is to investigate the practical aspects for building low-cost underwater swarm acoustic localization systems that can be widely deployed for civil application and scientific research in small-scale, near-shore environments. To achieve this goal, we define criteria for building such systems, review and compare existing swarm research and available techniques, instruments and tools, while providing direction and open questions for future research and applications. There has been a recent paper [14] that reviews advances in low-cost acoustic localization systems and acoustic modems from a practical point of view, and one [15] that addresses UUV localization with applications and practical use cases. However, their main focus is single vehicle localization systems. There are also reviews [17], [19] that cover the underwater localization techniques, while they conclude mainly the theoretical mechanisms and whether these techniques are transferable for swarm applications are not discussed. In work [15] localization techniques are reviewed with practical application cases for complex and confined environments. In [16] some acoustic modems and collaborative AUV localization methods are presented. General reviews for underwater swarm robotics include [20], [21]. Nevertheless, to the best knowledge of the authors, no work has discussed what constitutes a low-cost acoustic localization system for underwater vehicle swarms and the specific challenges, as well as whether existing localization methods are suitable for swarm localization solutions. Moreover, a lack of field demonstrations with UUV swarms [22] has been revealed by the literature which shows a large gap between the theory and real experiments in swarm localization research. Thus in this article, we aim to fill this gap by reviewing the recent underwater swarm acoustic localization systems for low-cost civil and research purposes, with aspects from choice of the UUVs, acoustic modems, evaluation tools and applicability of traditional localization methods for developing swarm localization systems in challenging shallow-water, near-shore environment, as well as identifying challenges, with the hope that this review will assist researchers with practical system building and inspire future work in this field.

This article is structured as following: Section II will present current applications of low-cost underwater swarm localization, which includes state-of-the-art low-cost underwater swarm projects and low-cost marine vehicles for building the swarm. Section III gives an overview of classic underwater acoustic localization methods and an analysis of these methods' applicability for low-cost swarm applications. Section IV focuses on the swarm acoustic localization methods which have been identified as applicable in the last section and presents several important aspects that should be considered for swarm localization systems. Section V summarizes simulation tools that provide test and evaluation platforms for localization solutions. Finally, the last section summarizes all discussed techniques and outlines open questions for future research.

II. APPLICATIONS FOR LOW-COST UNDERWATER SWARM LOCALIZATION

In this section we first give an overview of up-to-date research in low-cost underwater swarm applications. Then we introduce UUVs which are suitable for building low-cost underwater swarm localization systems.

A. UNDERWATER SWARM PROJECTS

A good amount of underwater swarm projects are dedicated for collaborative missions, such as underwater search and inspection, surveying and environment monitoring. While most projects only provide prototyping and simulation outcomes, very few have carried out practical in-field experiments, especially in regard of swarm localization, due to many technical aspects involved and difficulties of implementation in real conditions. Nevertheless we list some recent swarm projects which have implemented or show potential for swarm localization,with their timeline illustrated in **Fig. 2**.

First we discuss projects that are aimed for long-term ocean monitoring. A team of Mini-Autonomous Underwater Explorer (M-AUE) robots are developed for exploring submesoscale ocean dynamics [4] by researchers at University of California San Diego. A swarm of 16 independent robots are deployed to drift with the horizontal water flows and are capable of near-continuous underwater tracking. The 2D location of the subsurface vehicles are achieved by sending acoustic pings from synchronized and globally-localized surface floaters which are received by subsurface M-AUEs, together with the onboard depth sensor to provide the 3D position. The localization algorithm, however, is subject to clock drift and the localization result shows a few meters laterally drift over a $2\,\mathrm{km}$ track. In the EU Horizon 2020 FET project subCULTron a heterogeneous robotic swarm [23] with multiple Unmanned Surface Vehicles (USVs), a swarm of artificial fish and underwater sensor nodes are envisioned as an artificial marine ecosystem for long-term autonomous monitoring. The robots in the swarm are equipped with Inertial Measurement Unit (IMU) and Global Positioning System (GPS) for accurate localization, however, a localization strategy for the swarm is not implemented. Fields trials showed the formation control results of three vehicles, though the acoustic localization accuracy is not extensively analyzed.

There are also swarm projects for coastal and smaller areas. An inexpensive, trackable drifting robot swarm is built for mapping currents in coastal waterways in μFloat project [24]. The μFloat robots can move up and down through the ocean and also drift passively with the local water currents. The localization of subsurface robots are achieved by using acoustic modems equipped on GPS-tracked surface drifters. The Robotic Vessels as-a-Service (RoboVaas) project [2] aims to develop more efficient and safer maritime operations by delivering robotic-aided services like ship-hull inspection, quay-wall inspection and underwater environmental data collection. In the context of data collection [25], a swarm of USVs and AUVs equipped with acoustic modems and above water wireless links are deployed and communication protocols are developed to collect data from underwater static nodes, whereas the localization of the vehicles is not the focus of the project.

Biological inspiration has played an role in some swarm projects. In the BlueSwarm [26] project researchers developed a 3D swarm of fully-autonomous miniature (measuring $130\,\mathrm{mm}$ in the longest dimension) robots inspired by reef fish schools. A combination of cameras and blue-light emitting diodes give the fish-inspired highly-maneuverable Bluebots the capability of 3D vision and neighborhood sensing, while its actuation scheme with four independently controlled fins provide precise 3D locomotion and maneuverability and a

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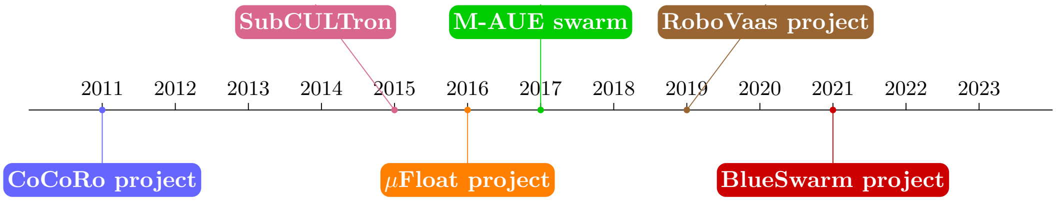

FIGURE 2. **The timeline of discussed underwater swarm projects.**

novel self-organized 3D coordination technique that achieves swarm formation behaviors. The EU CoCoRo project [27] proposed a cognitive swarm robotic system for efficient and autonomous search in the ocean. Inspired by the immune system, a small and affordable team of minature AUVs [28], [29] are built with both self-awareness and group-level awareness. The AUVs are equipped with blue light system for communication within the swarm, as well as acoustic sensing with the floating station for constraining the operation region.

B. UUV FOR LOW-COST SWARM LOCALIZATION

Various kinds of UUVs are developed for underwater missions and applications. UUVs can dive to sea bottoms, glide to the water surface, explore shallow water or hazardous areas where navigation is difficult. Depending on the intended use and applications, the size, shape and cost of swarm vehicles differ. In the scope of this article we focus on those that are on the low-cost end of the market, or developed by research institutes, which are also portable and require low deployment effort for the purpose of swarm localization.

Depending on with or without the presence of human intervention and tether, there are Remotely Operated Vehicles (ROVs) and AUVs. To help the swarm of robots navigate and localize themselves, USVs are often used together with UUVs. In the follows we will have a look on recently developed low-cost marine vehicles of these three types. A summarization of the mentioned vehicles can be found in **Table 1**.

1) AUVs

AUVs are autonomous UUVs that can work in an underwater mission without any human intervention or a tether. They offer a flexible alternative to traditional surface vessels.

In [30] A small, flexible and modular swarm-capable MONSUN AUV is developed by researchers from University of Lübeck. The MONSUN AUV has a length of $80\,\mathrm{cm}$, six brushless motors, and is designed for environmental monitoring, communication and agile navigation in swarm form. A micro AUV Hippocampus is deployed in [31] for self-localization in a confined marina environment. A fleet of torpedo-shaped low-cost micro AUVs (i.e., ecoSUBμ5) have been developed in [32] for undertaking missions including conventional applications like biogeochemistry measurements and ambitious ones like aerial launch for oil spill monitoring and polynyas accessing. A VENUS MAUV is a small AUV built by ENEA [33] that is equipped with a energy-saving strategy and both acoustic and optical modems. Some AUVs are bio-inspired, e.g. in an underwater swarm system H-SURF [34], a swarm of underwater robotic fish is developed. They are designed for monitoring wide areas and can interact and exchange information by acoustic and optical communications. The Quadroin AUV [35] from Evologics has a low-drag bionic design modeled after penguins. It is a high-speed AUV suitable for searching and is has been used in swarms for water currents monitoring.

2) ROVs

Underwater ROVs are usually operated by human pilots on land or surface vessels. A tether or umbilical cable links the ROV to a host which provides control signals and high bandwidth communication. Most ROVs are equipped with a camera, lights and thrusters, which allows it to transit live video stream back to the host computer. Some also has sensors like compass, IMU, odometer, pressure/depth sensor or Sound Navigation and Ranging (SONAR) on board to provide more measurement data.

The AC-ROV 100 [36] is a portable micro ROV that is capable of inspection in very small spaces. It is equipped with a camera and a limited payload of $200\,\mathrm{g}$. The Defender [37] from VideoRay is a highly customizable ROV capable of various configurations. It can be easily adapted for different target missions and has a depth rating up to $1000\,\mathrm{m}$. For battery-powered ROVs, some have tetherless capabilities, while it required the development of wireless control systems underwater. For example, Low-cost ROVs like BlueROV2 [12] has an intermediate size of less than $50\,\mathrm{cm}$ in length and $35\,\mathrm{cm}$ in width with operating depth of $100\,\mathrm{m}$, which has a great potential for swarm experiments with research purpose. EXRAY ROV [38] from Hydromea is a wireless underwater drone that is able to deliver live HD quality videos. The wireless control capability reduces the entanglement risks and significantly speeds up the inspection time. For the monitoring of nuclear waste ponds, the low-cost AVEXIS ROV [39] is developed by University of Manchester and has been deployed for the decommissioning of Fukushima nuclear power plant [40]. A gamma-ray detector is integrated within the ROV and the ability of collecting radiation measurements has been validated in real experiments [41].

TABLE 1. **Low-cost Marine Vehicles for Swarm Localization Applications.**

	Name	ROV/ AUV	Size	Depth Rating	Operation Time	Commercial/ Research
UUV	MONSUN AUV	AUV	0.8 m length	20 m	5 h	Research
	Hippocampus	AUV	0.45 m length	10 m	1 h	Research
	ecoSUBμ5	AUV	0.9 m length	500 m	24 h	Research
	VENUS AUV	AUV	1 m length × 0.2 m diameter	50 m	8 h	Research
	H-SURF	AUV	-	-	-	Research
	Quadroin	AUV	1 m length × 0.3 m diameter	150 m	10 h	Commercial
	AC-ROV 100	ROV	0.2 m length × 0.15 m width × 0.15 m height	100 m	-	Commercial
	Defender	ROV	0.75 m length × 0.4 m width × 0.27 m height	300 m	8 h	Commercial
	BlueROV2	ROV	0.46 m length × 0.34 m width × 0.25 m height	100 m	2 h–4 h	Commercial
	EXRAY	ROV	0.7 m length	50 m	6 h	Commercial
	AVEXIS	ROV	0.3 m length × 0.15 m diameter	10 m	-	Research
USV	SubNero SWANBOT		1 m length × 0.5 m width × 0.8 m height		-	Commercial
	H2Omini-X		1 m length × 0.9 m width × 0.4 m height		-	Commercial
	BlueBoat		1.2 m length × 0.93 m width × 0.46 m height		62 h	Commercial
	SeaML		<1.5 m length × <1 m width × <0.5 m height		8 h–12 h	Research
	BATDRON		1.65 m length × 0.6 m width × 0.34 m height		-	Research

3) USVs

USVs travels on water surface and are often deployed along with AUVs to accomplish collaborative missions. The benefits of USVs include mobility of the swarm operation and more communication possibilities. Usually a surface vessel or buoyancy is used as the surface node which provides global positioning from the satellite, and communicates with the submersibles using acoustic links which requires certain distance restraints with the underwater swarm. USVs, on the other hand, can travel with the swarm, thus providing mobility to the entire swarm and maintaining the communication. Radio Frequency (RF) communications and cellular network are possible if the vehicle is operated on a river/lake or close to the shore. For water quality monitoring, there is low-cost USV SubNero SWANBOT [42] which provides real-time monitoring and analysis of water quality at different depths. For seafloor and surface surveying, mapping and inspection, there is the modular multi-functional USV from H2O ROBOTICS, H2Omini-X [43], which is previously known as aPad in the EU H2020 subCULTron swarm [23] and plays the role of a connection to the terrestrial and the anchor in underwater localization. For hydrographic surveys and robotic platform development, there is BlueBoat [44], which is stated as the most affordable surface vessel that is capable of traveling in weed-filled lake and plastic-polluted waterways. USVs can also be used as a carrier for AUVs/ROVs and launch them in designated locations, e.g. the SeaML [45] from Fraunhofer CML are capable of both data collection and for deploying mini-ROVs. With a similar catamaran shape, the BATDRON [46] developed by Wroclaw University of Science and Technology is a low-cost USV system designed for bathymetric measurement, which provides similar level of measurement accuracy and less time compared to classic bathymetric missions performed on boat and pontoons.

III. UNDERWATER ACOUSTIC LOCALIZATION

In this section we introduce typical methods for acoustic localization and their potential for low-cost swarm applications. The underwater environment imposes substantial challenges on the means of communication and localization for swarm robots. Traditional RF communication methods is subject to strong attenuation underwater, which limits its propagation range. As a result, GPS positioning is only used for the surface anchors in underwater swarm localization. Other communication technologies like optical or magneto inductive are also subject to the limit of short range and water visibility, while acoustic communication shows broad potential for underwater communication in swarm localization especially for real-world applications. In general, acoustic localization relies on the Time of Flight (TOF) of sound propagating through water between referenced acoustic anchors and an acoustic modem or between modems.

In the acoustic localization literature, difference ways have been proposed to categories acoustic localization technologies [14]–[17]. In this work we adopt the three acoustic localization categories with difference sensor technologies: Acoustic Ranging, SONAR Simultaneously Localization and Mapping (SLAM) and Doppler Velocity Logs (DVLs). Although methods presented later are mostly applied for single AUV localization, their limits and potential for low-cost swarm localization will be discussed.

A. ACOUSTIC RANGING

Acoustic ranging is a technique that uses acoustic signals to estimate the distance between two acoustic devices. Here the acoustic devices refer to acoustic transducers which can contain both transmitters and receivers, or transmitters with a hydrophone.

Acoustic anchors (or called transceivers here) are widely used as reference points for acoustic positioning systems. Traditional acoustic positioning systems are categorized based on the anchors' positions, which are termed Long Baseline (LBL), Short Baseline (SBL), and Ultra-short Baseline (USBL) respectively. The recent development of acoustic modems allows acoustic localization without fixed anchors, which will mainly be introduced in IV-A.

1) Long Baseline (LBL)

A typical LBL systems contains transceivers which are placed over a wide area with baseline length from a hundred to thousands of meters. In such systems, the transceivers are fixed to the seafloor stations with relative or absolution seafloor coordinates [47] which are used as reference points for determining target positions. Target transponders, on the other hand, are mounted on positioning targets, for example, on surface vessels, AUVs, ROVs, etc.

LBL systems can also be combined with Inertial Navigation System (INS), which is called sparse-LBL. The LBL transponder is feeding the INS with a range to a referenced position, together with inertial sensors (gyroscopes, accelerometers) and other external sensors (depth, USBL, DVLs), enabling running a Kalman Filter to estimate the position of a target vehicle. Sparse-LBL is more flexible, cost-effective and can be used with reduced number of transceivers to achieve similar performance. Commercial LBL systems include Ramses from iXblue [48] which provides both conventional and sparse-LBL options, Teledyne LBL systems [49], Evologics S2C R LBL systems [50], etc.

The accuracy of LBL systems in general is from a few centimeters to less than one meter depending on the size of the node array and the baseline distance. They are usually deployed in locations where repeated operations are carried out, with the need of frequent battery replacement. Traditional LBL systems are usually not the first choice for swarm localization research, since these systems are expensive and demanding due to the long calibration process. For swarm localization applications, usually each agent in the swarm will receive response signals from all transceivers in a "round-robin" fashion, then use trilateration to calculate its own position. As a result, with conventional localization strategy, the communication effort will increase with the size of the swarm and the swarm position is updated until all agents in the swarm have received signals from all transceivers.

2) Short Baseline (SBL)

SBL system has several transceivers (i.e. anchors) that are mounted under a vessel or surface buoys with a baseline length from $20\,\mathrm{m}$ to $50\,\mathrm{m}$. The position is derived by the TOF of the signals received by the transceivers array. With a larger baseline, SBL systems can produce better positioning accuracy. Note that the receiver of the acoustic signals can also be transponders on moving UUVs, which is the case of swarm self-localization. Similar to the LBL systems, the propagation delay of the communication between the swarm vehicle and the anchors increase with the expending of the swarm size.

The Underwater GPS from WaterLinked [51] provides a SBL solution with an accuracy within $1\,\mathrm{m}$ at $100\,\mathrm{m}$ range. The accuracy of SBL systems is not fixed as USBL systems. With proper spacing of the transceivers, the precision and position robustness can be comparable with sea floor mounted LBL systems which makes it suitable for high precision survey work. When the transceiver spacing is limited or mounted on a small vessel then the precision would be reduced.

3) Ultra-Short Baseline (USBL)

A USBL system contains a transceiver, which is usually mounted on a pole under a vessel and contains several transducers with a baseline from a centimeter to decimeters. The transponders are attached to each target which can be fixed on seabed, or a moving UUV. The USBL system work in such a way that the transceiver sends acoustic signals and are responded by the transponders, which enables the transceiver to determine the TOF of transmitted signals from the time of transmission until the reception of the signals replied by the transponders. Then, the transceiver knows the distance (sometimes also bearings) towards the targets and can calculate the targets' positions. Finally to acquire the absolute positioning of the targets, the USBL system is often coupled to a GNSS system.

Commercial USBL systems include the Evologics S2C R USBL [52] that provides series of USBL systems with operating ranging from $1000\,\mathrm{m}$ to $10\,000\,\mathrm{m}$, which are suitable for various application like offshore equipment positioning, AUV/ROV navigation, diver/sensor tracking and undersea cartography. Compared to LBL, USBL is more cost-effective, though commercial systems are still in the high-cost league.

The USBL systems usually does not have the accuracy level of LBL systems. They usually have position error of 1–2 % of slant distance ($10\,\mathrm{m}$ to $20\,\mathrm{m}$ position error in $1000\,\mathrm{m}$ range), up to 0.04 % [53] in some ultimate systems. The flexibility makes USBL systems used from shallow water to deep waters (to more than $10\,000\,\mathrm{m}$) with small operational demand and continuous position estimation capability. Although the number of target UUVs is scalable, most cases the navigation computer is interfaced with the USBL transceiver on the vessel or a leading vehicle in the swarm. To achieve self-localization capability for all swarm vehicles, the USBL transceiver needs to be equipped on each vehicle.

B. SONAR SLAM

Sound Navigation and Ranging (SONAR) is one of the most important technologies of underwater acoustics. Most SONAR systems are used to detect and locate targets, e.g. submarines, fish or ships. There are two types of SONARs, active SONAR and passive SONAR. Active SONAR comprises a sound transmitter and a receiver. It transmits sounds waves of specific controlled frequencies, and listen for the reflections returned from remote objects. Passive SONAR can only receive sound signal and is unable to transmit their own. Mostly referred SONARs are active SONARs. Active SONARs that calculate distances to objects by measuring TOF of ping signal are ranging SONARs, while those that capture acoustic images as scans are imaging

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TABLE 2. Applicability of conventional acoustic methods for low-cost swarm localization in terms of several swarm localization attributes. "+" indicates good, "−" poor and "○" reasonable applicability for low-cost swarm localization.

	Self-Localization	Cost		Scalability	Accuracy	Communication
	Swarm	Price	Deployment	Swarm Size	Position	Overhead
LBL	+	−	−	+	+	−
SBL	+	+	+	+	○	−
USBL	○	○	+	+	○	+
SONAR SLAM	+	−	+	○	−	+
DVL	+	−	+	+	−	+

SONARs [17]. Most common types of ranging SONARs include echo sounder, mechanically scanned profiler and multibeam echo sounder. Analogously, common imaging SONARs include mechanicaly scanned imaging SONAR, forward-looking imaging SONAR and sidescan SONAR. Active SONARs have the capability to extract information from the underwater environment without the constraint of clear water, which makes them most suitable for underwater SLAM [54].

Some SONAR SLAM systems have been developed recently for exploration tasks in complex underwater environment with small AUVs. SUNFISH [55] is a person-portable 6-DOF hovering AUV that is capable of robust online SLAM using its multibeam SONAR and a dead-reckoning system based on an IMU, an acoustic DVL and pressure depth sensors. SVIn2 [56] is a recent SLAM system specially targeted for underwater environment like wrecks and underwater caves, with easily adaptable sensor configurations with a mechanical scanning profiling SONAR, camera, inertial and depth sensors. In [57] authors combine convolutional neural network (CNN) generated overhead images with SONAR images from the AUV and integrate them into a pose SLAM framework, which shows the potentials for applications such as hull inspection, harbor security and operating near offshore structures. Most SONAR SLAM projects are not low-cost, since usually IMU/DVL/USBL are combined with SONAR to compensate for the increasing error of SLAM solutions. Moreover, there has been few swarm SONAR SLAM research, given the technical challenge of developing robust swarm SLAM solutions.

C. DOPPLER VELOCITY LOG

DVL determines the velocity vector for a moving AUV by sending acoustic signals towards the sea bottom and capture the echoes. Usually four SONAR beams are transmitted in a downward direction, with each beam pointing in a different angle. The velocity of the vehicle is estimated by combining the Doppler shifts of each sound beams.

DVL offers an accurate estimate of velocity with zero-mean bias. Since DVL estimates velocity relative to the sea bottom, it must be within the range of the bottom to maintain bottom tracking and thus accurate navigation. While DVL can be used to provide stand-alone Dead Reckoning (DR) localization solutions, it is prone to error over time. In fact, DVL is usually used in conjunction with another most common DR sensor INS, to correct the accumulated error due to the integration of INS measurements. For long range missions when AUV cannot use acoustic positioning for navigation, DVL in combination with INS is commonly used as the navigation sensor . Commercial DVLs offers small size, long range and reliable navigation (e.g. distance error of 0.13% is report with WaterLinked DVL during 295 m traverse [58]). Nevertheless, main drawbacks such as high cost and drift over time hinter the use of DVLs in low-cost swarm applications.

D. DISCUSSION

Acoustic localization can be carried out in different ways depending on the types of operations underwater, the cost and accuracy required for the operation (e.g. whether accurate geo-referenced positions over a long distance is needed with frequent update). For example, a long-range subsea survey requires the highest accuracy of localization, with highest cost, while a diver would want a low-cost lightweight solution with moderate accuracy. The challenge lies in the trade-off between the requirements of the application such as the task length, maximum allowed localization error and the cost, size, weight and power consumption of the devices. Thus it is important to be well informed of the current technologies which is most suitable and affordable for specific underwater tasks. In the rest of this paper, we decide to focus on low-cost acoustic localization solutions for AUV swarms in the context of low-cost research-oriented applications in small-scale environments like port areas and shallow water, using low-cost, person-portable devices. Accordingly, the swarm localization solution should cater for several attributes including, the self-localization ability for each agent of the swarm, the cost (including price and deployment cost of chosen system), whether the swarm is scalable, the accuracy of the localization result and whether there is communication overhead. Tailored for these specific attributes, **Table 2** shows the applicability of introduced conventional acoustic localization methods.

IV. LOW-COST UNDERWATER SWARM ACOUSTIC LOCALIZATION

In this section we investigate low-cost swarm acoustic localization methods. It is worth mentioning the criteria brought

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up in [59] for a multi-robot system to be considered as a swarm: first, the system consists of homogeneous agents with a controller dealing with the whole swarm; second, scalability and redundancy given by multiple agents; third, each robot has limited sensing and communication abilities. Combined with the applicability of acoustic systems in **Table 2** , we conclude that the systems that fit with the application scope of this work should at least show applicability with the "Scalability" and "Cost". As for the "Self-Localization" ability for the swarm, there are generally two scenarios referred to in some literature as the leader-follower scheme and the parallel scheme [16]. Similar to the centralized and decentralized terms for control system, the leader-follower localization scheme is more "centralized", where the follower AUVs only talk with the leader AUV and not with each other. Since high-precision sensors are only equipped on the leader AUV (e.g. USBL [60]) and low-precision sensors are equipped on follower AUVs, the scheme is often used for reduced cost and communication needs. However, the drawbacks of such systems include failure of localization of whole swarm when the leader is lost and only the leader has the absolute position information of all AUVs, thus the self-localization of follower AUVs is not achieved. On the other hand, in the parallel scheme, each AUV is equipped with same sensors to precisely localize themselves and to communicate with other AUVs. The parallel scheme makes the swarm more robust to the failure of a single unit due to the decentralization, where self-localization of each AUV can be achieved. Nevertheless, it is still a challenge to avoid message collision and develop efficient localization communication protocols to provide continuous and accurate position update, despite the high latency due to low speed of sound [61]. With the above discussion in mind, in this section we focus on the underwater swarm localization systems that utilize low-cost acoustic sensors and are able to provide self-localization for each swarm agent in a decentralized way.

The recent development of low-cost acoustic modems makes range-based localization for AUV swarms more achievable. When considering localization with a team of AUVs, many aspects should be considered compared to single AUV localization. First, self-localization of each AUV in the swarm is necessary for the successful swarm navigation. Also, we need to consider the limited acoustic communication between multiple AUVs, while avoiding message collisions if agents try to communicate simultaneously. Moreover, the data measured by all AUVs has to be accurately referenced to a geographic location with accurate time in a common or own time frame.

A plethora of localization algorithms for UWSNs have been developed and different categorizations of research have been reviewed in recent works [16], [18], [19]. Recently, state-of-the-art low-cost acoustic localization systems have also been reviewed in [14]. To the best of our knowledge, there has not been work reviewing the current acoustic localization methods for AUV swarms using affordable acoustic modems and underwater robots for research applications. This paper aims to fill this gap by presenting current low-cost swarm acoustic localization methods with real applications, discussing challenges and important aspects, while trying to identify possible future research directions for the research community.

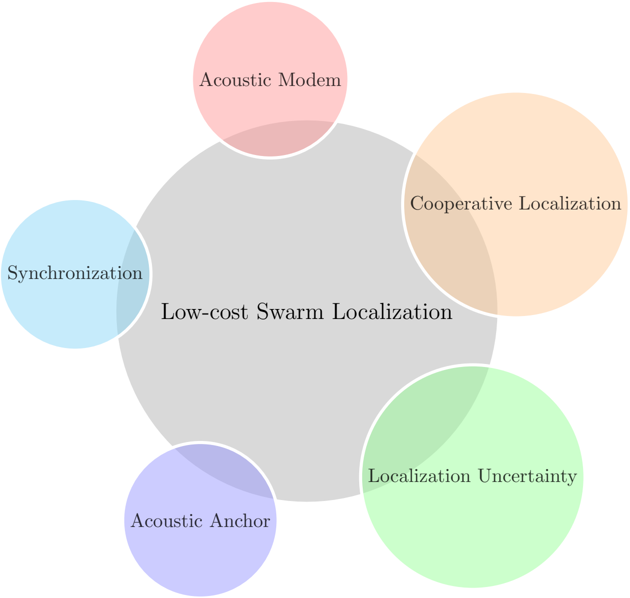

FIGURE 3. **The discussed aspects of AUV swarm acoustic localization.**

We will discuss in this section the acoustic range-based localization for a swarm of AUVs from the following aspects: firstly, we introduce low cost acoustic modems suitable for underwater swarm localization systems. Secondly, for range-based swarm localization schemes, the TOF measurements are distinguished by One-way Travel Time (OWTT) and Two-way Travel Time (TWTT) depending on whether synchronization is needed for the agents in a swarm. Then, similar to single AUV localization, current work that uses acoustic anchors for AUV swarm localization, which can be categorized by fixed anchors and moving anchors, are discussed. Next, we address the uncertainty issue for swarm acoustic localization. Last but not least, we introduce recent research work with cooperative localization strategies. The structure of this section is shown in **Fig. 3**.

A. LOW-COST ACOUSTIC MODEM

Underwater acoustic modem is the most common underwater wireless technique for an Underwater Wireless Sensor Network (UWSN). With the development of acoustic modems, stationary anchors have no longer been mandatory and full AUV autonomy can be achieved using autonomous vehicles equipped with acoustic modems [17]. A comprehensive review about the state-of-the-art acoustic modems can be found in [14].

When multiple vehicles are communicating with each other with acoustic modems in an UWSN, dedicated media access methods are crucial to prevent collision of packets and for the self-localization of swarm vehicles. Due to bandwidth restrictions, localization protocols also share the same channel as the communication protocols to produce optimal amount of traffic for vehicles to localize in the swarm. Several modems provide software frameworks that provide software modules for implementing communication protocols, e.g. the ahoi modem [62] allows access to its firmware which enables both built-in Media Access Control (MAC) protocols and tests of tailored protocols. The open source EviNS framework [63] can be run directly on the Evologics acoustic modems' hardware where not only several MAC and routing protocols are available, but users can design own solutions on it.

With the popularity of small-scale AUVs utilized in research, the capability of acoustic modems to be integrated in such swarm AUVs has been important for localization. In [14] several low-cost acoustic modems which are utilized by low-cost underwater robots in real-world scenarios are mentioned, e.g. the Nanomodem [64], [65] development by Newcastle University is used in [66] for the localization of a swarm of ecoSUB AUVs [32]. In a trial where the AUV travels around the perimeter of a $50\,\mathrm{m} \times 50\,\mathrm{m}$ square area, TWTT is measured for inter-node acoustic range measurement in its network-based localization algorithm [67] and passed to an Extended Kalman Filter (EKF) for the estimation of the AUV positions. The accuracy of their localization method is however missing, due to the lack of ground truth while the vehicle is submerged.

The low-cost ahoi modem [62] is developed by researchers from Hamburg University of Technology. It has been used in field experiments in harbor area [31], [68], where in [68] the authors show that a moving BlueROV2 is localized with positioning error below $75\,\mathrm{cm}$ in an operation range below $30\,\mathrm{m}$ using an EKF for the position estimation and RTK-GPS as reference. In an AUV swarm localization scenario with a leader-follower formation [60], the authors show that an acceptable accuracy can be achieved by using ahoi modems in a low-cost multimodal low frequency (LF) and high frequency (HF) acoustic network (MM). In the proposed MM network, a surface node and a leader AUV are equipped with LF acoustic modems and USBL capabilities, while four follower AUVs and the leader can communicate with HF ahoi modems. The leader AUV estimates its own position by communicating with the surface node which has a GPS receiver, and can measure distances to follower AUVs using TWTT and relative speed by measuring Doppler effect. An Unscented Kalman Filter (UKF) is implemented for the leader to estimate the state of the full system while the follower AUVs has no information of their absolute positions due to no direct contact with the surface node. Thus a regular recalibration is carried out for each AUV to estimate its position by a triangulation process. Simulations using DESERT Underwater simulator [69] show that a tracking error of below $5\,\mathrm{m}$ for a close follower AUV and $13\,\mathrm{m}$ for a far follower AUV can be achieved when AUVs have $54\,\mathrm{m}$ distance between each other during the mission. Although there have been no field experiments carried out yet with ahoi modems for swarm AUV localization, they have shown great potential and suitability for the deployment on micro and small-sized AUV swarms benefiting from their small-size, low-cost, customizable and easily reproducible characteristics [62].

The SeaModem [70] is a low-cost acoustic modem for shallow water communication, which is developed by AppliCon, a spin-off of University of Calabria. It is used in [71] for the localization of a moving target diver using SBL system where four modems are equipped on a surface platform together with a GPS receiver and an IMU, and an acoustic modem on the target diver. The localization errors are analyzed for each device utilized in the OWTT localization scenario and the measured data is merged in an EKF. The simulated localization results show a total positioning error of circa $2\,\mathrm{m}$ using real data collected from a $15\,\mathrm{m} \times 15\,\mathrm{m}$ square area track. Statistical analysis of the error sources are carried out which shows their impact on the total positioning error and can be optimized to improve the accuracy of the localization system.

A custom made transducer developed by researchers in University of Michigan is introduced in [72]. The range measurement between a transmitter and a receiver is evaluated in a freshwater pool within $1.5\,\mathrm{m}$ range and shows a $15\,\mathrm{cm}$ offset to the ground truth which could be due to processing delay. In simulations, the acoustic OWTT based range is fused with visual odometry and a dead reckoning system in a pose graph framework [73] for low-cost micro AUV localization, where the acoustic ranging information is shown to provide significant improvement to the position estimation, achieving circa $1\,\mathrm{m}$ position error in a lawn survey in a $20\,\mathrm{m} \times 60\,\mathrm{m}$ area. Nevertheless, there is no further real-world evaluation of this localization solution.

A small-sized acoustic transceiver is developed in [74] and equipped on miniture AUVs (VERTEX AUV [75]) as receiver and USVs as transmitters for a OWTT-based multi-AUV navigation system. GNSS Pulse Per Second (PPS) timing is used for synchronizing clocks of AUVs while they are on the surface and for transmitting ranging pulses and positions from USVs. In their experiments real data is collected at a shallow lake, with two USVs deployed as surface anchors while one is moving, and one USV used as a surrogate for an AUV. The trajectory of the AUV is estimated with an EKF fusing inertial position estimates and ranging measurement in offline simulations, where a Root Mean Squared (RMS) error of circa $1.6\,\mathrm{m}$ is achieved in an operation over circa $15\,\mathrm{m} \times 30\,\mathrm{m}$ region. Their work in [76] which has a similar experiment setup also uses factor graph for the post-processing of to the EKF estimated trajectory to get a smoothed consistent trajectory.

The above mentioned low-cost modems are mostly developed by research groups for SBL and LBL systems (referred to modern LBL systems, whose attributes are different from Table 2, but with positive price applicability). One limitation of these systems is the time and cost of setting up a network of anchors. USBL systems, on the other hand, only needs one acoustic anchor containing a transceiver array which is easier to deploy. There are also some low-cost USBL systems developed recently like the OWTT inverted USBL system in [77], and the Seatrac modem/USBL system in [78]. The summarization of mentioned acoustic modems can be found in Table 3.

B. SYNCHRONIZATION

An important aspect in underwater swarm localization is whether time synchronization is needed for vehicles in the swarm. The surface sensor nodes can be time-synchronized by using GPS, while the underwater sensor nodes cannot, and the clocks of underwater nodes are subject to skew and offsets. Depending on if synchronization is needed or not, there are in general two ways to acquire range measurement from the submerged AUVs, namely One-way Ranging (OWR) and Two-way Ranging (TWR).

1) Synchronized OWR

OWR utilizes the OWTT. Such systems usually use acoustic anchors and AUVs with strict time-synchronization, using a precise clock, suck as a miniature atomic clock or an Oven-controlled Crystal Oscillator (OCXO). Different from the traditional setup (e.g. in section III-A) where the target position is calculated by the operator/base station, here we mainly focus on the case where AUVs are able to self-localize, which means that AUVs are the receivers of acoustic packets with the packet transmission time encoded.

There are two types of OWTT schemes for OWR. One type uses the Time of Arrival (TOA) of acoustic packets emitted by acoustic anchors which is recorded by each AUV of the swarm. The OWTT is thus calculated as the subtraction of the arrival time and initiation time and the relative range is determined as the product of the OWTT and the speed of sound (approximately $1500\,\mathrm{m/s}$). Usually three anchors are needed for the TOA and trilateration is applied for the localization of the AUV in 2D case. The other type uses the Time Difference of Arrival (TDOA) where the time difference between the measurements of the different anchors is taken. Only the synchronization between the anchors are required and at least four anchors are needed for the AUV localization.

OWR requires only a single packet transmission between the target AUV and the anchors, but requires AUVs to go to the water surface for the synchronization signals [16] or the use of precise crystal oscillators. In [79] the authors use Chip Scale Atomic Clock (CSAC) to perform OWR and keep a precise measure for up to a few weeks of missions. Although CSAC are very accurate and have a very low power consumption, they are very expensive (over $5000\,\mathrm{euro}$), making them not suitable for low-cost AUVs. In [80] a OWR method is proposed for the ranging of a swarm of robots and evaluated in simulation. In the simulation each AUV in the swarm periodically broadcast a packet with its transmission time according to the Time Division Multiple Access (TDMA) protocol so that other robots receiving the packet will know the relative distance. The work in [81] presents the development of an underwater localization system for a flexible number of AUVs. Multiple AUVs and a Spiral Wave Front Beacon are used and the vehicle clocks are sychronized with the beacon in the beginning and during the long mission. The positioning of the underwater AUV is estimated with a distributed Kalman algorithm and in-field experiments show that the proposed OWR methods achieve a minimum standard deviation of $0.11\,\mathrm{m}$. Authors of [74] present a multi-USV system to provide positioning aid for underwater environmental sampling missions with AUVs in lakes and coastal areas. The system achieves scalability in the number of AUVs by using OWTT for ranging and makes the AUVs passive receivers.

2) Unsynchronized TWR

Two-way Ranging (TWR) systems use the TWTT, which is the TOF for an acoustic signal to be emitted by an AUV to reach an anchor and then a response signal from the anchor to return to the sender [82]. TWR ranging does not require each robot/anchor in the swarm to synchronize with each other, but is subject to an issue of slower update rate since the acoustic signal has to travel twice between two agents in the swarm. It can be problematic when the vehicles are far away from each other and could lead to localization errors when the vehicles are moving while communicating.

TWR is typically used in SBL/LBL systems for AUV self-localization. Net-LBL [83] is a LBL system with four acoustic modems deployed statically on the seabed. In a sea trial in the Gulf of La Spezia, Italy, a mobile node with acoustic modem is deployed on a rubber boat as the localization target and the TWR method is used when it communicates with the static nodes using two MAC protocols. When dealing with one vehicle positioning, there has been research that takes into consideration the vehicle motion. In [84], the authors proposed a ROS-based underwater robot simulator which simulates acoustic TWR considering the vehicle motion during signal propagation. Other study achieves acceptable localization accuracy with TWR and filtering techniques to compensate for the vehicle motion. For example, the work in [68] presents a TWR scheme for a BlueROV2 with RTK-GNSS ground truth with centmeter accuracy. The authors utilize a standard EKF with a linear 2D-constant-velocity model for the ROV's position estimation. This study uses ahoi modems [62] which are integrated in the ROV and two buoys deployed at a marina and the real-experiments with operation range of $30\,\mathrm{m}$ show that the TWR localization algorithm can achieve a localization accuracy of the moving ROV below 1 meter with a localization update rate of 1 Hz. This work, however, only estimates the AUV position offline with collected date, thus online capability of the algorithm is missing.

TWR has also been used for swarm AUV applications. In [30], a communication principal for 2 surface AUVs and various number of dived AUVs are proposed using TWR between the GPS-localized surface vehicles and the dived ones, in order for the dived AUVs to get relative distance information and maintain a V-shaped formation. The position update rate decreases linearly with the number of dived AUVs in the swarm which limits the scalability. In [67] a network-based

TABLE 3. **Low-cost acoustic modems with localization solutions.**

Modem / Author	Work	System	Sync.	Anchors	Algorithm	Experiment	Region	Range resolution	Accuracy	Swarm Localization
Nanomodem [64], [65]	[66]	LBL	TWTT	3 fixed	DR & EKF	Sea trial, 1 ecoSUB	50 m × 50 m	10 cm	No ground truth	Capable [67]
Ahoi modem [62]	[31]	LBL	TWTT	4 fixed	EKF	Marina, 1 BlueROV2	70 m × 70 m		1.36 m RMS (GPS: 2.5 m CEP)	-
	[68]	SBL	TWTT	2 fixed	EKF	Marina, 1 BlueROV2	25 m × 25 m	6 cm	35 cm (GPS-RTK)	-
	[60]	USBL, LBL/SBL	TWTT	1 moving	UKF	Simulation	1500 m× 400 m	-	<5 m	Capable
SeaModem [70]	[71]	SBL	OWTT	4 fixed	EKF	Simulation	20 m × 20 m	-	2 m (GPS accuracy 0.1 m–3.5 m)	-
Ruland et al. [72]	[72]	Visual, LBL	OWTT	2 fixed	Pose graph [73]	Simulation	30 m × 60 m	-	1 m–3 m RMS	-
Quraishi et al. [74]	[74]	SBL	OWTT	2 moving	EKF	Shallow water	30 m × 15 m	-	1.66 m RMS	Capable
	[76]	SBL	OWTT	2 moving	EFK, factor graph	Shallow water	30 m × 20 m	-	2.1 m RMS	Capable

localization strategy is proposed for an underwater acoustic network, where the time information of TWR is transmitted in acoustic messages. The transmission effort scales linearly with the number of AUVs while the frequency depends on the MAC protocol of the network. Furthermore, the resolution of the range measurement is limited by the relative clock drift depending on the available hardware (1.5 m resolution in a TDMA-based network with 60 s frame). The network was tested in a sea trial with an operation range of a square of 7.5 km × 7.5 km, using high-end acoustic modems, two AUVs, together with INS, DVL and GPS data to provide the ground truth. The average range error of the network-based navigation method is betweem -9 m and 3 m, with a maximum error of 90 m. Nevertheless, the accuracy of this method conducted in a low-cost trial as mentioned in IV-A above is not available.

C. ACOUSTIC ANCHOR

Acoustic anchors are the default localization technology for ocean-based systems [15]. Also termed as beacon in the literature, acoustic anchor serves as a global reference for the self-localization of AUVs. In most cases the position of acoustic anchors are either tracked by onboard GNSS antennas or georeferenced before the underwater mission. Not only can acoustic anchors be installed deep in the seabed, the suitability of acoustic anchors in marinas, harbors and boatyards is also high. Although anchor-free localization methods exist, it is not common in the context of swarm applications because the restriction of the movement of vehicles. There are commonly two types of anchors: fixed anchors and moving anchors.

1) Fixed Anchors

Acoustic positioning with fixed anchors is a classical wave propagation and triangulation problem. The localization system measures the TOF of acoustic signal takes to travel between the fixed transducer and the vehicle and can, therefore, estimate the distance between the transducer and the vehicle. One main attraction of localization using fixed anchors is that the position is referenced to physical devices that are fixed in space. The drawback is that, the accuracy of localization is reliant on accurately knowing the position of fixed transducers in a global coordinates. Thus, one incorrect transducer position has considerable impact on the overall accuracy of the system.

Classical LBL systems utilize fixed anchors at the seafloor or mooring buoyancy in deep sea. The drawbacks of such systems are the limits of operational range of a few square kilometers and heavy deployment effort which reduce the advantage of using AUVs [59]. Fixed anchors are widely used for underwater swarm projects. In the M-AUE system [4], five surface floats are deployed as surface anchors which can provide precise GPS positions by sending ping signals with its submerged acoustic transducer for the subsurface M-AUE vehicles to estimate their own positions. The work in [85] similarly uses 2 buoys fixed to a pier with precise RTK-GNSS positioning and integrated acoustic modems for the localization of a BlueROV2. In [86] a novel localization methods is proposed for a sparse UWSN using a small number of anchor nodes. Distance from sensor nodes to anchors are estimated hop by hop using trilateration and weighted least squares.

2) Moving Anchors

Moving anchors enable the AUV swarm to explore larger area in the ocean rather than in confined areas. There exists research work where single and multiple anchors are used for swarm localization. In [87] a low-cost navigation technique is proposed for AUV swarms that uses a leader AUV with an anchor and estimate the following AUVs' positions by measuring Doppler shift and attenuation difference. The accurate position of the leader anchor could be acquired either from dead reckoning method with INS/DVL or from GNSS source.

A surface vehicle can be used as a moving anchor that localizes itself with GNSS and broadcasts its position for the localization of dived AUVs. As a result, there is no need to georeference the anchors before missions, which is more time and energy efficient [17]. In the subCULTron Underwater Acoustic Sensor Networks [23], the aPad surface vehicles provide GPS localization, WiFi modems for communication above water and a low-cost acoustic modem to enable localization of underwater nodes. In a coordinated navigation method with USVs and AUVs [88], the USVs are used as the "satellite" for the AUVs by fusing GPS solution and a USBL solution. Both the AUVs and USVs are equipped with the SeaTrac USBL system for two-way communication. In [30], 2 surface AUVs in a swarm are used to provide GPS positioning through acoustic two-way communication to dived AUVs, which allows the dived AUV to know the relative distance and follow the surface AUVs in a specified formation. The work in [74] use USVs as moving anchors and provide a solution for multi-AUV localization.

D. LOCALIZATION UNCERTAINTY

To achieve high accuracy localization, the uncertainty of the localization system has to be accounted. For range-based localization, the TOF information of acoustic signals are measured and the distance is estimated as the product of the speed of sound in water and the TOF of the signal traveling between two devices. One key source of uncertainty, therefore, is the range estimation which is affected by the inaccuracy of sound speed and the precision of the TOF measurement. The varying sound speed underwater can be determined by the sound speed profile (SSP), which depends on depth, temperature, salinity, daily/seasonal cycles and space. Without measuring the sound speed, the accuracy of distance measurements based on TOF approaches may be degraded [89]. In addition, the uncertainty of TOF measurement is affected by non-perfect synchronization of clocks, possible clock drift between devices and the misalignment between the sender/receiver timestamps and the actual signal emission/reception time (or, delay in the computation by microprocessor).

Not only the accuracy of range measurement, but the following aspects will contribute to the uncertainty of the localization performance.

a: ***Latency***

Underwater acoustic localization is inevitably affected by latency due to TOF: the time needed for the sound signal to travel between the vehicle and reference points. In other words, the propagation delay will cause a latency for the localization results. As a result, the update rate of the swarm localization can even be slower if it is required for each vehicle in the swarm to update their positions in a round of ranging measurement, depending on the complexity of the localization algorithm, propagation latency and the swarm size. This will produce errors in ranging measurements too when the targeted vehicle is moving at the same time. The motion of the devices during the signal transmission and propagation will affect the accuracy of ranging measurement due to the biased TOF measurement.

b: ***Vehicle motion***

The localization uncertainty due to motion of robots depends on the robot speed and the latency due to signal transmission and propagation. In a relatively small environment the latency remains low, e.g. with a nominal sound speed $1500\,\mathrm{m/s}$ and $10\,\mathrm{m}$ distance, the two-way TOF is approximately $13\,\mathrm{ms}$. However, in a larger environment, the latency will be considerably larger where the localization offset due to robot movement becomes larger.

c: ***Drifting***

While it is reasonable to assume that nodes in terrestrial networks remain static, underwater nodes will inevitably drift due to underwater currents, winds, shipping activity, etc. Nodes may drift differently as the current is spatially dependent. While reference nodes attached to surface buoys can be precisely located through GPS updates, it is difficult to maintain submerged underwater nodes at precise locations. This may affect localization accuracy. One source of underwater positioning drift is the movement of the ambient ocean currents. The actual ocean currents are affected by factors like wind and temperature, which is hard to accurately represent [90]. Nevertheless, there are ocean current models presented recently, e.g. in [91], [92].

The drift-caused position change will inevitably affect the accuracy of localization systems where the AUVs receive the global positions of anchors before the mission and assume them static during the mission. Thus another critical technical challenge is to update the AUVs about the real-time positions of the anchors, which is necessary in systems using moving USVs. Moreover, the classic metric Geometric Dilution of Precision (GDOP) for evaluating the uncertainty of trilateration position fixes assumes precise knowledge of anchor positions, thus has neglected the impact of anchor position errors, which should be addressed [93].

E. COOPERATIVE LOCALIZATION

Cooperative localization allows a swarm of vehicles to localize within themselves. This is especially useful for applications in an open area where the swarm forms large underwater sensor networks.

Traditional filtering approaches such as EKF and Particle Filter (PF) marginalize past poses, thus discarding information. Due to the computational efficiency and the benefit of fusing multiple sensor modalities, variants of EKF are most commonly used as solutions for swarm localization. A pose graph on the other hand incorporates all the measurements and past poses and formulates the localization problem as that of global optimization over all states. While this is computationally more expensive it provides smoother trajectories and lower errors in presence of non-linearities. [72]

Depending on the cooperation strategies, it is worth mentioning that the literature distinguishes different strategies as single-stage and multi-stage [18], some as organic cooperation and hierarchical cooperation [93] or absolute localization and relative localization [59]. In general, in the former strategy, each vehicle directly communicates with reference anchors for its self-localization and does not support localizing other vehicles in the swarm, while in the second strategy, one or several vehicles localize themselves and then serve as new reference anchors for localizing rest vehicles. The hierarchical strategy may benefit from larger coverage and reduced communication, though it can suffer from uncertainty propagation since the position error of first-localized vehicles will translate directly to the position estimation of later-localized vehicles.

A few works have addressed the acoustic localization problem for a cooperative team of a few number of AUVs. In [93] hierarchical cooperative strategies are presented with USVs to provide GPS positioning, AUVs that self-localize using the USV position information and a single-beacon cooperative navigation (CN) algorithm. An adaptive positioning algorithm has been proposed which shows that the AUVs' position uncertainty is minimized by adapting the position of the USVs. Moreover, a distributed algorithm is developed for all anchor vehicles that enables joint minimization of uncertainty of all receiving vehicles. The results from sea trials show that the proposed CN provides lower AUV position errors than the EKF and PF. A distributed cooperative localization system for AUV teams is proposed in [94]. The acoustic-only localization network adopts a TDMA communication protocol and each node in the network employs an EKF for fusing IMU and acoustic measurement (one fixed control station is equipped with USBL to provide better position estimation for other vehicles) and can estimate positions of itself and other nodes. In a sea trail test in a shallow lake, a network of an AUV and two fixed nodes are deployed and the result shows that USBL node is able to localize other nodes with error within $0.3\,\mathrm{m}$. It has also been emphasized by the authors that the localization performance is strongly dependent on acoustic communication capabilities.

The development of smart mobile sensor network that provides node localization as a service for an existent acoustic network was discussed in [66]. A fleet of small and low cost AUVs (i.e., ecoSUB [32]) is utilized, where range measurements aided DR navigation is implemented for node localization [83]. In [95], a fuzzy cooperative localization framework is proposed for underwater robot swarms. The proposed localization framework utilizes fuzzy logic for information fusion, which has inherent advantages over EKF-based fusion, such as design simplicity and flexibility. Unlike EKF-based fusion which requires dynamic motion models, Gaussian error models, and major changes in the motion models in the case of integrating additional sensory information, new knowledge can be acquired and represented in additional fuzzy rules or modifying rules in the fuzzy localization framework. In [80] the authors propose a cooperative underwater acoustic ranging method for a swarm of vehicles and use an underwater network simulator DESERT [91] for the simulation and evaluation of the ranging results. The proposed cooperative ranging strategy requires minimum transmission of packets between the swarm and no time synchronization, however, the ranging accuracy is reduced drastically when there is packet loss thus not applicable for real experiments. Although the communication protocol is subject to failure, the design of the efficient localization protocol is inspiring for swarm localization.

V. UNDERWATER LOCALIZATION SIMULATOR

For evaluating the localization algorithms for the underwater swarm, simulation is a meaningful tool when it can produce trustable results. Sea trials are high-cost and prone to failure in the development phase for swarm localization protocols, thus testing and evaluating the localization algorithms with underwater network simulator is the optimal way before investing the effort for deploying a large network of vehicles and sensors. Especially for underwater swarm localization, an efficient underwater simulator should address the following needs:

1) **Underwater Network Stack Modeling**: that contains the complete network stack which enables development of MAC protocols for swarm localization. A low-cost swarm localization strategy should address the communication and networking among swarm vehicles efficiently.
2) **Underwater Physical Layer Simulation**: which models the physical characteristics of the UWSN in underwater environments, including interfaces with actual devices (e.g. acoustic modem drivers). Detailed aspects of physical layer capabilities of underwater simulators are listed in [84].
3) **Emulation Capability**: that enables the same code used in simulation to be used in wireless testbeds. It offers code reusability and reduces the work moving from simulation to deploying the protocols in sea trials.
4) **Robot Mobility and Ranging Modeling**: which provides the measurements for acoustic range-based localization and tracks the movement of vehicles.

Numerous underwater network simulation tools have been developed, while few have the ability of simulating both the underwater communication network and ranging among the

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TABLE 4. Underwater Simulators for Swarm Localization.

	Network Stack			Physical Layer			Emulation	Mobility & Ranging		ROS		Availability
	ns2-MIRACLE	*ns3*	*Other*	*Acoustic*	*Optical*	*Multi-modality*	*Capable*	*Node Mobility*	*Acoustic Ranging*	*Robot Model*	*Visualization*	*Open-source*
DESERT [91], [96]	✓	-	-	✓	✓	✓	✓	✓	✓	-	-	✓
SUNSET v2 [97]	✓	-	-	✓	-	-	✓	✓	✓	-	-	✓
Aqua-Sim NG [98]	-	✓	-	✓	-	✓	-	✓	✓	-	-	✓
UAN [99]	-	✓	-	✓	-	-	-	✓	✓	-	-	✓
UnetStack3 [100]	-	-	✓	✓	-	-	✓	✓	✓	-	-	✓
CCA [101]	-	-	✓	✓	✓	✓	✓	✓	✓	-	-	-
UWRange [84]	-	-	✓	✓	-	-	-	✓	✓	-	✓	✓
UWSim-NET [102]	-	✓	-	✓	-	-	✓	✓	✓	✓	✓	✓

underwater nodes. The open-source framework DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols (DESERT Underwater) [91], [96] is an underwater network simulator based on the MIRACLE extensions [103] of the open source network simulator ns2 [104]. It provides not only multi-modality network capabilities with acoustic and optical communication, but also underwater ranging and mobility modules which support simulation, emulation and sea trials for the design and implementation of underwater localization protocols. The SUNSET version 2.0 framework [97], based on ns2-MIRACLE [105], supports simulation, emulation and real-life testing with position sharing capability. Aqua-Sim Next Generation [98] is a ns3-based [106] underwater sensor network simulator which provides emulation capability, as well as synchronization and localization modules in higher protocol layer. The ns3 UAN [99] framework is an underwater network simulator which includes an AUV mobility model. The UnetStack3 framework [100] offers an underwater network simulator for developing and testing underwater network protocols, as well as a ranging service that supports one-way and two-way ranging between nodes. The CCA framework [101] is a modular architecture which is developed to be a multi-modal, flexible and secure underwater network. It is designed to support quick "operational prototyping" for in-filed experimentation, with cooperative ranging utility for vehicle navigation.

Some simulators have integrated Robot Operating Systems (ROS) which provide both robot dynamics simulation and the visualization of its mobility. However, the capability of robot swarm positioning is still a scarce feature in ROS-based underwater simulators. UWRange [84] is an open source ROS-based acoustic ranging simulator for micro AUV localization. It extends current underwater robot ROS simulator with acoustic ranging characteristics considering vehicle motion and is capable of simulating range measurement under real-world link qualities. Nevertheless, it does not address the underwater localization problem for a swarm of vehicles. UWSim-NET [102] extends the ROS-based underwater robotic simulator UWSim [107] by integrating an ns3-based communication module which allows to simulate both Aqua-Sim NG acoustic modems and custom modems. UWSim-Net can perform real-time simulations of robots and the underwater network. A teleoperation with a real BlueROV [108] shows its capability of performing ranging measurement in a swarm of cooperative robots. A summary of related underwater simulators with the addressed aspects is presented in **Table 4**.

VI. CONCLUSION AND OUTLOOK

In this article we provide a review of low-cost underwater swarm acoustic localization systems, particularly presenting current research which has been evaluated by field experiments. We first introduce low-cost swarm localization applications including suitable low-cost UUVs, as well as recent advance of underwater swarm projects. Then classic acoustic localization strategies are presented with their applicability analysis for low-cost applications ideal for research purposes. Next, we give a comprehensive review on important aspects of identified applicable acoustic swarm localization systems for low-cost applications. Lastly, we define good underwater simulator attributes and summarize suitable simulation tools for developing and testing low-cost underwater swarm localization solutions The aims of the design of low-cost swarm acoustic localization can be summarized as: using low-cost portable devices; developing a flexible network structure with low-delay communication; achieving reliable message transmission for swarm safety and exploration missions.

In Section IV, we especially review recent research with low-cost LBL / SBL / USBL localization systems and several critical issues in swarm localization. Although all the three systems have restraint operation range due to the geometry of pre-deployed anchors and the limited range of the acoustic communication, the alternative USVs seem to be a promising way to expand the mission area and provide more motion flexibility to the swarm. For swarm localization systems using TWR, longer propagation time results in a slower localization update, and the design of the localization protocol may affect the scalability of the swarm. An efficient MAC protocols, as well as localization algorithms, therefore, is needed to provide a fast swarm localization update. In addition, we discuss different sources of uncertainty for swarm localization in Section IV-D, and the [93] in Section IV-E shows the cross-correlated uncertainty of vehicle positions in a cooperative localization system with hierarchical structure. This has posed an open research question of how to design cooperative localization schemes which minimize / bound the uncertainty of all agents in the swarm. The formation of the swarm is another issue which is indicated to affect the swarm localization uncertainty. Other than that, these desired properties [109] of swarm cooperative localization need also to be fulfilled during the system development: high accuracy, low cost, efficient communication, robustness against faulty sensors, wide coverage, good scalability, bounded uncertainty, fast convergence, consistency, etc.

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