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Communication for Underwater Robots: Recent Trends

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Abstract

Purpose of Review Underwater robot communication – both between underwater robots and between other nodes and stations out of the water – is essential for intelligent cooperative behaviors and for enabling high-impact applications such as ocean monitoring and exploration, surveillance, and pollution cleaning. This paper surveys recent literature on underwater communication with a specific focus on underwater robots and their autonomy with the objective of identifying recent research trends, open challenges, and future directions.

Recent Findings From out-of-the-water communication, underwater communication presents unique challenges, including low bandwidth of the communication channel and the lack of reliable communication infrastructure. Current research has looked at reducing the cost of the devices, designing more realistic communication models, and including those models in robot planning.

Summary While current efforts have made progress on underwater communication systems for supporting robotics autonomy, reliable communication for long-term operations remains an open problem. Exciting research directions, including but not limited to simpler communication configuration, selective information sharing, and graceful recovery, emerge from this survey, which can contribute towards heterogeneous robotic systems that can be deployed for the exploration of the underwater world.

Keywords Underwater communication · Heterogeneous multi-robot/agent systems

Introduction

The objective of this paper is to identify recent trends and open problems in *underwater communication* that can enable robot autonomy.

The aquatic world plays a critical role in our society, as 70% of the Earth is covered by water. It helps in regulating climate [1], providing drinking water, and supporting agriculture [2]. However, 95% of the ocean is still not explored and charted [3], limiting our understanding of the aquatic world and its impact in our environment, as well as preventing the development of effective policies for supporting the blue economy [4].

Underwater robots can significantly advance the exploration of the underwater world [5]. To date, *ad hoc* aquatic robots have been used in scientific expeditions and specialized applications, such as for containing oil spills [6–8]. One of the challenges in using underwater robots includes the very complicated logistics necessary for such expeditions. A research vessel – with a daily rate of US$10k to US$40k [9] – is necessary to deploy expensive underwater robots (that cost in the order of US$100k to US$1 M [10]). In most cases, such deployments need trained pilots to control the Remotely Operated Vehicles (ROVs) or experts to plan a mission for the AUVs to execute [11]. Another type of deployments relies on the use of underwater drifters [12] that share information at specified surfacing intervals. In general, underwater robot deployments, compared to above the water, present several more challenges, including the fact that there is no GPS and no Wi-Fi infrastructure, limiting the application of robotics technology underwater [13]. There is however interest in developing effective underwater communication technologies from different parties, including the US Navy [14].

This survey paper analyzes recent literature on underwater robotics communication, a fundamental enabler for scaling up exploration and intervention with multiple robots [15,

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16]. First, we provide a brief historical overview of underwater communication; then, we present recent trends of related research together with open problems and future directions. In particular, there are two communication channels that are typically necessary for underwater operations: (1) completely underwater to enable communication between underwater assets and (2) underwater-air so that underwater robots can communicate with on-land resources such as base stations – see Fig. 1.

Brief Historical Overview of Underwater Communication

Many commercially available underwater robots are ROVs, which typically rely on a tether for communication, connected to a mother ship [17]. Different types of tethers are available, including coaxial, twisted pairs, and fiber-optic. Each type provides different characteristics in terms of cost, maximum length, flexibility, and speed [18]. Such vehicles have been used for marine science expeditions, oil and gas operations, etc. Clearly, a tether, while providing a reliable connection, restricts the motion of the robot, potentially creating an entanglement hazard.

Autonomous underwater vehicles (AUVs), typically shaped as a torpedo, have been developed without any tether, providing a way to survey large areas. In many cases, AUVs are programmed to follow specific missions without any communication during the mission. In other cases, sharing of information happens at pre-determined times, by letting the robots surface and acquire satellite communication and localization [19]. Some research considers systems of units that are not communicating with each other, such as inexpensive drifters deployed [20–23] to collect data. Other research has also looked at ways to have an implicit communication, by sensing other robots' behavior towards swarm robotics [24]. Some notable examples include fish-like robots or bio-inspired behaviors for AUVs that communicate through sensing other robots positions [25–27]. Currently, the main information shared in real time among robots that explicitly coordinate include navigational updates from the surface or the status of the AUVs [13, 28]. More data-heavy information, such as video feed, is typically not shared due to the limited bandwidth of current underwater communication technologies. Mainstream communication systems rely on acoustics to allow communication between underwater vehicles and operators. One of the main advantages of acoustics is the possible long range, in the order of kilometers. The downside is the high noise and low bandwidth – in the order of kb/s. In addition, acoustic systems require good calibration of the sound velocity, as such systems are affected by difference in temperature, as well as multipath effects [29]. Optical communications based on directional laser or LEDs instead can support up to hundreds of Mb/s within tens of meters [30], requiring precise tracking. While communication based on electromagnetic waves is the main wireless communication mode out of the water, underwater it is not common, as the signal attenuates very quickly, especially in seawater [31]. Some small-scale sensor networks have used RF-based communication underwater, for example to support a small-scale sensor network in shallow areas at the bottom [32]. Some researchers considered air/surface/underwater communica-

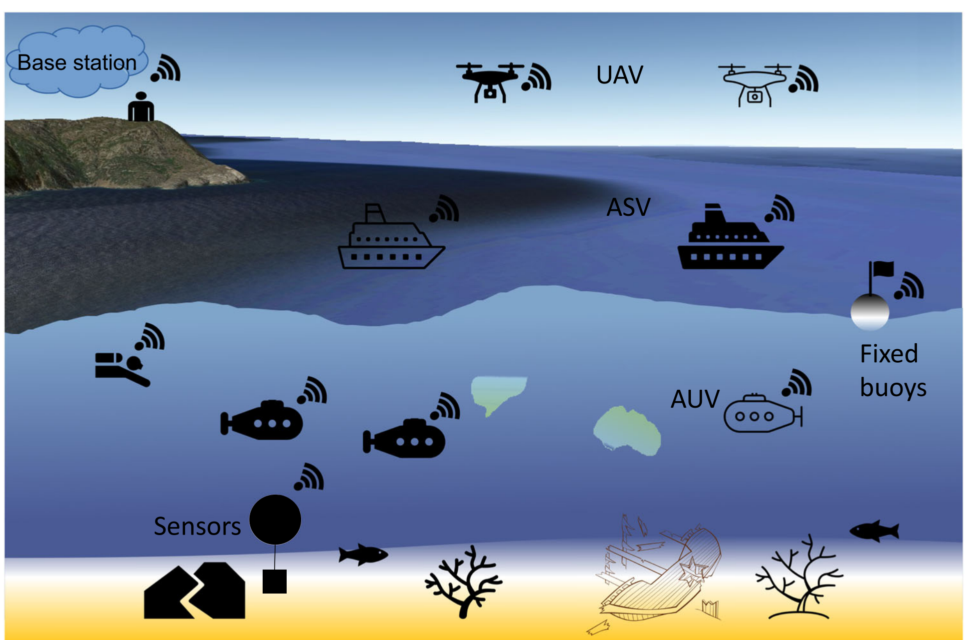

Fig. 1 Scenario with base stations, Unmanned Aerial Vehicles, Autonomous Surface Vehicles, fixed buoys, Autonomous Underwater Vehicles, fixed underwater sensors, and divers for accomplishing an underwater task requiring communication

tion with the underwater robot surfacing from time to time to connect to the air/surface robot [33, 34]. Note that, commonly, research and commercial products have considered point-to-point communication [35], limiting the increase of the number of robots within a team.

Table 1 shows a concise overview of the communication technologies that can be found in commercial underwater operations. The overall cost of such devices is in the order of thousands or tens of thousands US$. Each of them has its strengths and weaknesses [30]. Note that there are at least two other useful quantitative metrics from the robotics perspective that are dependent on a number of factors, including the desired rate and range: *power consumption* and *latency*. A qualitative characterization of them show that the both power consumption and latency are higher for acoustic, while lower for optical [36]. In addition, optical communication technology is not fully established yet, with fewer commercial products (e.g., [37–39]) available compared to the acoustic counterpart (e.g., [40–46]). In fact, there are recent optical communication prototypes that demonstrated hundreds of Mbps data rate in a distance of over 200 m [47] to tens of Gbps within ten meters [48].

There have been surveys on underwater communication for underwater sensor networks, with nodes that could be fixed or mobile. They have focused on the low-level aspects of communication, including signal processing algorithms, modulation and coding schemes of acoustics [49–55] and light-based communication systems [36, 56, 57]. A recent survey discussed strengths and weaknesses of RF, optical, or acoustic systems [30, 31]. A 2015-survey [58] looked at the current gaps in securing underwater acoustic sensor networks. There have been also works in detecting acoustic communication for military applications [59]. Another recent survey looked at AUVs supporting underwater sensor networks in data collection. Relatively fewer surveys have discussed underwater systems in the context of navigation or formation [19, 60, 61]. A general overview on communications in multi-robot systems is presented by Gielis et al. [62].

This survey will bridge the gap between communication and robotics with the goal of unveiling current trends and challenges in the context of enabling underwater autonomous operations with mobile robots and other assets.

Recent Trends

Research in underwater communication to support robot operations have looked at different subproblems in the last five years: 1) the physical communication systems and protocols to decrease the cost and increase the bandwidth, range, and reliability; 2) communication strategies that explicitly consider the communication constraints; 3) robot control and planning to improve the overall communication network; 4) realistic communication simulations to advance robotics algorithms; 5) communication across air-water to remove the need of surface devices.

More Realistic Channel Characterization

Recent works have looked at improving the realism of channel models. Many papers particularly focused on light-based communication, with only a few on acoustics. Jamali et al. [63] studied external factors such as turbulence that have an impact on the channel. In addition, the paper investigated multiple-input multiple-output (MIMO) tranmission for mitigating such factors. Hamza et al. [64] analyzed the impact that environmental noise such as solar radiation has on optical communication systems underwater at shallow depths. A generic analytical model is presented together with an analysis of different photo-detector types. Elamassie et al. [65] proposed a closed-form path loss model that explicitly considers water type, beam divergence angle, and receiver aperture. Numerical experiments validated the proposed models, identifying bounds on bit error rates and showing that MIMO techniques can compensate for external factors and increase total transmitted power and support longer distances. As this model showed through simulation that the achievable distances are in the order of tens of meters, the paper tested a multi-hop system to guarantee an end-to-end bit error rate for a given number of hops and observed that

Table 1 Different underwater communication technologies with the corresponding data rate, range, main application in robotics, and commercial availability

Communication type	Communication technology	Data Rate	Range	Use	Availability
Tether	twisted cables (ethernet)	up to 10 Gbps	up to 100 m	control/navigation/video	Commercial
	Optical fiber	up to 10 Tbps	up to 10 km	control/navigation/video	Commercial
Wireless	Acoustic	up to 10 kbps	up to 1 km	control/navigation	Commercial
	Optical	up to 100 Mbps	up to 100 m	control/navigation/video	Research/Few commercial
	Radio	up to 10 Mbps	up to 1 m	control/navigation	Research

Note that the achieved data rate is dependent on the chosen communication range: a longer range would decrease the data rate. Also note that optical communication typically requires clear water, while radio and acoustic can also work in turbid water the relation between number of hops and achievable distance is not linear. Bernard and Bouvet [66] proposed an acoustic communication protocol optimized for multiple users, based on chirp spread spectrum, improving the performance over conventional code-division multiple access and time-division multiple access.

Simulators have been researched to achieve a higher degree of fidelity so that experiments can run even before testing the systems and algorithms in the field. The availability of datasets helped in achieving more realistic simulators. Otnes et al. [67] discussed the validation of acoustic channel simulators based on a dataset collected in a Norwegian fjord. Looking at bit error rate, the study found that the simulator qualitatively followed the real data, with a relatively small error. Sources of errors include channel estimation errors, simulation approximation, and statistical fluctuations. Coccolo et al. [68] introduced a simulator that adds noise generated by vessels and AUVs within the range of the acoustic network. The method is based on a lookup table for specific AUVs and closed-form models for ship vessels. Casari et al. [69] provided a dataset for underwater network emulation with different topologies so that it can become a standard benchmark to test different scheduling protocols. Campagnaro et al. [70] developed a statistical channel model from real field experimental data to account for different environmental conditions and improve the realism of the simulations. Kexin and Chitre [71] proposed a machine-learning based model for ocean acoustic propagation when limited information is available about the environment.

Lower-Cost Communication Devices

Another trend that can be observed in recent years is the increase in the number of communication devices that are less expensive than the current ones, trading off for range or bandwidth. Renner et al. [72] developed a 600 US$ open source acoustic modem that can be mounted on micro AUVs and can communicate at distances of 150 m. Chen et al. [73••] proposed the use of microphones and speakers from regular smartphones to enable inexpensive communication underwater. Jang and Adib [74•] presented a backscatter networking based on piezoelectric effect at nearly zero power consumption. Their experiments in water tanks showed single-link throughputs at 3 kbps and range up to 10 m. Based on the similar principle of acoustic backscatter for communication, a very recent work [75] designed an underwater camera system that doesn't require a battery to operate allowing for long-term sensing operations. Cossu et al. [76] designed an underwater optical communication system composed of common LEDs as transmitter and achieved 10 Mbps, up to 7.5 m with minimum packet loss in real sea environment. Hanff et al. [77] designed a micro AUV that uses an optical communication module developed in-house to fit into the very small housing of the robot. The paper shows a data rate of 19 kbps at a range of around 2.5 m. Schill et al. [78] presented an underwater robotic platform aimed for achieving a swarm of robots. Communication modules include a very-low-frequency radio that can get up to a few meters in water and an optical communication system with higher bandwidth, but still low range. Distributed algorithms to ensure a fair access to the limited channel were implemented. Lin et al. [79] presented a prototype with off-the-shelf components for underwater communication based on lights, where circularly polarized and double links are used to make the visible light communication system more robust to environmental interference such as sunlight. The experiments in the pool, lake, and sea show a data rate in the order of hundreds of kbps at a distance of a few meters.

Recently, software-defined modems have appeared in the underwater domain to provide a high-degree of flexibility and reconfigurability for different scenarios. Lin et al. [80••] proposed a Software-Defined-Network based architecture for AUVs, where the network operator can program the network control through a uniform programming interface by using a centralized SDN. The proposed architecture divides the low-level data layer, the local control layer for the robots, and the main control layer with a base station. The proposed system has been tested in simulation. Coccolo et al. [81] performed experiments to test a software-defined modem in a very shallow canal, demonstrating the abilities of SDM platforms to perform all transmissions in real time.

Mixing of Communication Technologies

While most of the works focused on a single communication mode, there have been a few proposals mixing both acoustic and optical communication devices to complement their strengths and optimize the energy consumption.

Han et al. [82•] presented a hybrid acoustic/optical solution to enable real-time video streaming, where the acoustic channel is used as a backup when there is an interruption (e.g., misalignment) of the optical communication. The work also provided a compression technique for images that allowed a smooth transition between the two communication channels. Experiments in a small tank are performed to validate the proposed approach. Yan et al. [83] proposed a two-stage solution for data collection over an underwater sensor network: first, low-capable sensor nodes transfer data to a short-range data collector through acoustic communication; second, AUVs visit the data collectors and download data with a light-based communication link. The proposed solution optimizes the energy usage across the system. Simulation results show its effectiveness in increasing the overall network lifetime.

This multimodal underwater network pushed the expansion of existing simulators. For example, Francescon et al.

[84] extended their underwater simulator to support acoustic and optical devices, as well as surface WiFi links.

Cross-Medium Communication

While most of the research focused on communication completely underwater, recent works have looked at enabling wireless communication between air and underwater without the need of surface devices. Tonolini and Adib [85••] proposed a system based on an acoustic transmitter underwater and a radar-based receiver out of the water. The vibration caused by the sound at the surface allows the radar receiver to pick up the signal. The developed prototype was shown to have hundreds of bits per second with distance up to tens of centimeters. The work [79] described earlier using the circularly polarized light for more robust light-based communication tested also the air-water communication by moving the receiver out of the water while keeping the transmitter (blue LED light) in the water. The experiment showed that, while in the water the data rate was at 190 kbps, just out of the water (2 m total distance, with the receiver moved at around 50 cm from the water surface), the data rate drops to 145 kbps. Carver et al. [86••] developed a laser-based communication system equipped with a MEMS mirror and fisheye lens to allow steering of the laser-beam to the receiver. An array of ultrasonic sensors is introduced to detect waves and account for waves. Experiments in a water tank and a swimming pool showed a throughput of 5 Mbps and a range of up to 6 m. While the work of Carver et al. [87•] focused primarily on the localization of an underwater robot with an aerial drone, there is an interesting communication component based on a laser-optimized backscatter design, allowing the robots to share localization information between air-water, without the need for any intermediate node.

Explicit Communication Modeling in Robot Operations

Given the unique challenges in underwater communication, research has been pushed in the direction of identifying robotic algorithms to cope with such challenges. Early on, Arrichiello et al. [88] experimentally looked at the effects of communication on the control of underwater robotic teams, with the goal of informing the development of new control strategies. Abichandani et al. [89] developed a path coordination method based on mixed integer non-linear programming that accounts for a number of constraints, including communication connectivity. Simulations were performed to show the ability of the proposed method to find collision-free and improved-connectivity trajectories. Al-Khatib et al. [90] presented an overview of a European project called "Widely scalable Mobile Underwater Sonar Technology" (WiMUST), with the goal of developing a system of cooperative AUVs for surveying and exploration. Specific to communication, the project aims at addressing long-range and short-range communication challenges in the context of formation control. The modem that was considered is the one developed by EvoLogics which achieved a significant increase in bit rates from several hundred of bits per second to kilobits per second. Paull et al. [91] proposed a cooperative SLAM framework where communication is efficient: packets are generated with a size that has a linear relation with the number of observed features, is constant with the number of AUVs, and does not grow with time. Simulations are performed to validate the proposed algorithm, improving the overall localization error. Khan et al. [92] described a mechanism for data collection of underwater sensor nodes that allows for efficient management of energy and bandwidth. The proposed method is based on clustering of the nodes and a fixed time slot intracluster communication. Simulated experiments show that the proposed method extends the network lifetime. Tsiogkas et al. [93] and Allotta et al. [94] developed a multi-robot task allocation method when AUVs communicate with high latency and packet loss, by building a distributed world model. Millán et al. [95] showed a control strategy that guarantees robustness against communication disturbances, by using a feed-forward controller. Simulations validated the proposed formation control performance. Ferri et al. [96] illustrated a framework where AUVs need to track objects underwater with cooperative algorithms that use local information to decide on whether to deviate from the initial mission. Experiments were conducted at sea, showing how cooperative autonomy improved the tracking capability of the robots.

In some scenarios, communication constraints involve ensuring communication between underwater and surface vehicles. McMahon and Plaku [97] designed a sampling-based method that is able to find locations for the AUV to collect data, at the same time ensuring that the communication is maintained with the ASV.

While most of the current work looked at explicit information sharing, research has looked at hardware solutions co-designed with the algorithm. Fischell et al. [98] developed a swarm robotic system where the leader has a single transducer as a multi-frequency sound source and the followers carry a low-cost acoustic device to adapt the navigation according to the Doppler-shifted frequency and range.

Future Directions

Current research attempts at pushing underwater communication to enable robots' autonomy, so that the models are more realistic, the devices are lower cost than before, and robots consider such factors in their planning. Generally, research in underwater communication is necessary to handle larger teams of robots to be able to cover the extent of the ocean that is still unknown. This is generally shown to be important, as suggested by a recent survey [99] on multi-robot exploration.

Some interesting research directions are highlighted below.

Simpler Communication Infrastructure for Real-World Operations A ubiquitous underwater communication network for cyber-physical systems that is simple and flexible to set up as WiFi networks is still not available. Bulky devices are typically necessary which also can hinder the operations of small low-cost AUVs. Human divers also have limited options to communicate with the robots, with the mainstream communication being tags or gesture [100–102]. A few options are also available for air-water communication. Simpler communication infrastructure should be designed, both in terms of hardware and software, to support underwater operations of many nodes. In addition, most of the research tested the communication protocols in simulation; however, it is important to validate the proposed approaches in a real scenario to ensure their working condition in the wild.

Selective Information Sharing Continuous broadcasting could result in the saturation of the communication channel and robots' loss [103]. Generally, information shared among robots can have a positive impact on the task execution [104, 105]; however, it is not yet fully clear what the actual relationship is between shared information and performance. New methods for identifying the importance of the information shared and accordingly selecting them can help in making the best use of the limited communication channel for autonomous operations, so that a specified Quality-of-Service can be guaranteed [106]. Furthermore, the resolution of the shared information could be tuned according to the available bandwidth, as shown for example in [107] where the scene map quality is adapted.

Resilient Communication The literature on ensuring robust network of ground/flying robots studied a routing protocol that takes into account the robots' mobility [108–110]; how the robots should move in the environment to preserve connectivity with teammates [111–113]; and recover from connectivity disruption [114, 115]. Some other work proposed algorithms to ensure the continuation of the task [116, 117], or to determine rendezvous locations [118–120], considering fixed roles or without addressing the recovery of the failing robot. These methods assume that a failure results in the loss of one or more robots and focus on the recovery of the whole system. Given the high cost of the underwater devices and the importance of the data collected, which might be available only locally to the robot, until the mission is over, it is important to devise recovery mechanisms that allow robots to gracefully degrade so that robots do not fail completely.

Defined Experimental Protocols The experimental protocols in underwater communication are not yet fully standardized, thus limiting the reproducibility and repeatability that are necessary to validate proposed methods. Simulators, which are the mainstream approach to test underwater communication strategies, can be limited in their realism. Defining experimental protocols in standardized scenarios, open-sourcing the hardware design and code, and sharing the data can contribute towards reproducible and repeatable results.

Conclusions

Underwater communication is fundamental for enabling a widespread deployments of multi-robot systems to support high-impact societal applications, such as ocean exploration and monitoring. This paper has highlighted the most recent work and trends in underwater communication, from both the networking and robotics communities. This overview allowed the identification of research directions towards reliable underwater communication. Most notably, current effort attempts at reducing the cost of the devices, considering more realistic models, and including those models in the robot planning. Effort should be spent on guaranteeing resilient communication, so that underwater robots can be effectively deployed in the real world.

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Compliance with ethical standards

Conflicts of interest The authors declare that they do not have any conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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