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Survey on Low-Cost Underwater Sensor Networks: From Niche Applications to Everyday Use

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Abstract: Traditionally, underwater acoustic modems and positioning systems were developed for military and Oil & Gas industries, that require deep water deployments and extremely reliable systems, focusing on high power expensive systems and leaving the use of low-cost devices only attractive for academic studies. Conversely, recent developments of low-cost unmanned vehicles, such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), suitable for shallow water coastal missions, and the need of sensors network deployments for measuring water quality and studying the effect of climate change in coastal areas, called to the need of low-cost and low-power acoustic modems and positioning systems that are gaining more and more momentum to date. The use of these devices can enable a wide set of applications, often based on low-cost AUV swarm formations, where an acoustic link between the vehicles is required to coordinate the mission, perform the maneuvers, and maintain the formation along the time. Moreover, they can make environmental wireless sensor deployment cost effective by substituting wired systems. Underwater positioning systems, usually used in large-scale operations, can be finally applied to small-scale application thanks to the reduction in costs, at the price of a lower transmission and positioning range and precision. While in open-sea application this performance reduction is a huge limitation, in river, lagoon, port and lake deployments this is not an issue, given that the extremely shallow water and the presence of many obstacles would deteriorate the acoustic signal anyway, not allowing long range transmissions even with expensive and sophisticated acoustic devices. In this paper, we review the recent developments of low-cost and low-power acoustic communication and positioning systems, both analyzing University prototypes and new commercial devices available in the market, identifying advantages and limitations of these devices, and we describe potential new applications that can be enabled by these systems.

Keywords: underwater acoustic networks; underwater acoustic positioning system; underwater low-cost assets; underwater monitoring; review

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1. Introduction

The high power consumption and the high cost of traditional commercial acoustic modems [1–3] and positioning systems [4–6], typically used in military and offshore deep water deployments, makes them unaffordable for many civil applications, such as development of underwater internet of things (UIoT) sensor networks for monitoring the water quality of bathing and aquaculture sites [7] and ports [8], and for observing the biodiversity of a certain area. In addition, their use in low-cost remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) is prohibitive due to the fact that the price of a low-cost underwater vehicle, such as the BlueROV [9] (that costs less than 5000 EUR), is approximately half of the cost of modems equipped with ultra-short baseline acoustic positioning systems (USBLs). The recent availability of these low-cost unmanned vehicles [9,10] and the introduction of new sensor technologies applicable to smart ports [8] and aquaculture sites [7], called for new developments of both industries [11] and research institutes [12] that, in the last five years, focused their effort on realizing low-cost and low-power acoustic modems and positioning systems, rather than following the previous research trend of further increasing transmission range, datarate and ranging accuracy. In fact, the requirements of the aforementioned applications in terms of communication range and datarate are not as stringent as the one needed for surveillance and offshore applications, and also the maximum depth of the deployment in this coastal applications is typically a few tens of meters, instead of the several hundreds of meters or even several kilometers deployments used in offshore applications: this enables the possibility to use low-depth rated casing and therefore reducing the cost of development and materials. These new coastal civil applications (Figure 1) require simple and affordable devices that can be powered with small batteries, such as smartphone power-banks. New products are now available, all characterized by a cost of less than 1000 EUR, a maximum power consumption of approximately 1 W, in transmission, and 100 mW in reception, and able to transmit and perform ranging operations up to a few hundreds meters at a datarate between a few tens [11,13,14] and a few hundreds [12,15,16] of bits per second.

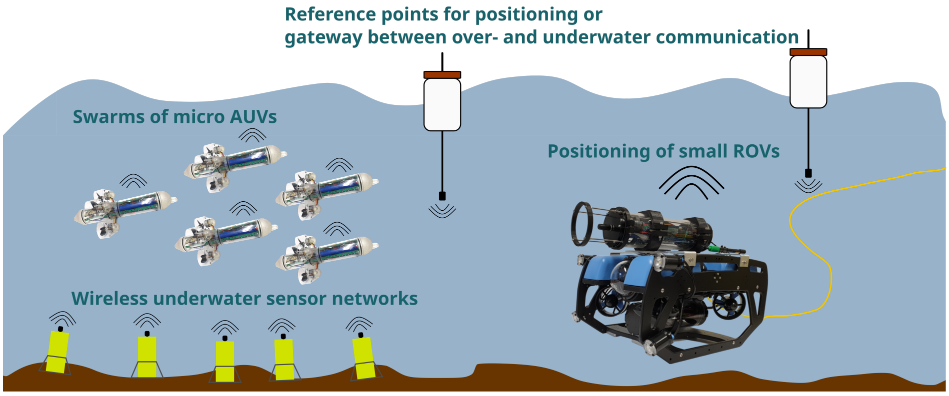


Figure 1. New applications enabled by low-cost underwater modems and positioning systems. Abbreviations: autonomous underwater vehicle (AUV), remotely operated vehicle (ROV).

The main contribution of this paper is the complete and updated review of these affordable devices, their comparison with legacy acoustic modems, and the discussion of potential applications enabled by low-cost acoustic modems and positioning systems. Most of the previous survey papers focus on acoustic communication, networking and positioning for offshore applications e.g., [17–19]. The authors in [20,21] provide extensive reviews of acoustic underwater modems. Although in both works the authors mentioned small-scale acoustic modems for low-cost applications, recent developments have not been discussed, as the survey presented in [20] reviews articles up to 2015 and the one in [21] articles up to 2018. Underwater positioning systems are discussed in [22] for confined environments, e.g., industrial tanks or nuclear storage facilities. In [23,24] underwater navigation and localization systems are analyzed. These surveys provide an overview of different systems and acoustic positioning is presented very briefly.

This article investigates whether or not in the near future underwater networks can be used in civil applications for everyday use. To answer this question a complete review of the state-of-the-art of low-cost acoustic modems and their potential applications is carried out. The information inserted in this review is mainly based on direct experience of the authors, given that both the Hamburg University of Technology and the University of Padova developed prototypes of low-cost acoustic modems. This development required the authors to be constantly updated on the most novel research trends related to this argument, making them becoming quite experienced in the field of low-cost acoustic modems. In fact, the literature survey performed by the authors is based not only on a web research using the most common research engines, where key words such as “low-cost acoustic modems” have been searched, but also on the knowledge gained by the authors attending tens of international conferences and workshops on underwater communication in the last five years, exploiting these events to exchange ideas and information with many research fellows operating in this area. In sum, we added 123 references to this survey. The references include 37 internet links and 86 scientific papers. 45 papers cover acoustic modems and positioning systems. The other 41 papers examine applications and previous surveys. Figure 2 depicts the distribution of publication dates for all papers and those with acoustic modems and positioning systems. More than 51% of the cited papers were published during the last 5 years.

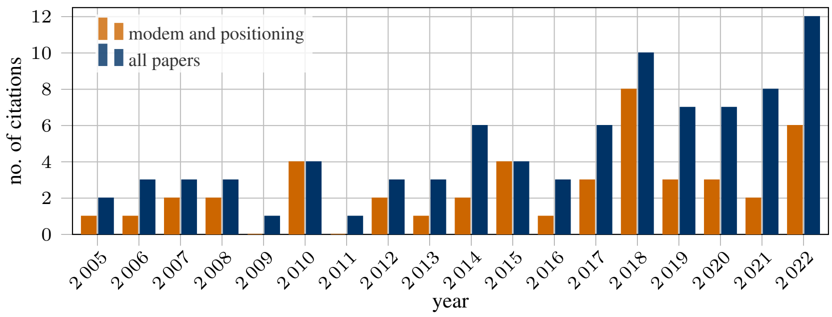


Figure 2. Cited scientific papers compared to the publication date. In sum, 86 scientific papers are discussed in this paper. 45 papers cover acoustic modems and positioning systems and 41 papers examine applications and previous surveys.

This paper is structured as follows. Section 2 presents a review of the currently available low-cost acoustic modems, while newly available acoustic positioning systems are discussed in Section 3. Section 4 presents new potential applications enabled by these new acoustic communication and positioning devices in light of the recent development in underwater robotics, sensor and navigation systems. Moreover, the same section presents the limitations of the current technology and tries to identify what is still missing to bring underwater networks to the mainstream. Finally, Section 5 draws our concluding remarks.

2. Underwater Acoustic Modems

In this section, after introducing the various underwater communication technologies (Section 2.1), we review the state of art of acoustic modems, starting from a discussion of the acoustic modem used in legacy offshore and military operations (Section 2.2) and then reviewing low-cost acoustic modems for UIoT (Section 2.3) applications.

2.1. Introduction to Underwater Wireless Communication

Four underwater wireless communication technologies are available to date, namely underwater electromagnetic radio frequency (RF), magneto-inductive, optical and acoustic communication [25]. Given the high attenuation of electromagnetic signals, especially in salty water, regular WiFi, cellular and satellite technologies cannot be used to perform long range transmissions underwater. Very Low Frequency (VLF) and Extremely Low frequency (ELF) RF antennas were used during the Cold War to enable communication from an over water base station to submarines, transmitting with very low bitrate and with a very high-power consumption. While VLF deployments allow communication up to a depth of 20 m below the sea surface, ELF systems have global coverage but require an antenna with a size of tens of kilometers and to irradiate 2 W of power they require a power consumption of 1 MW [26]. Given that ELF and VLF installations are very expensive, only a few countries in the world had those type of systems: almost all of them are currently dismissed. Conversely, today a few small high-rate (order of a few Mbps) low range (up to 1–2 m) commercial RF modems are used in AUV docking stations and for a few other specific applications [27]. Magneto-inductive modems, instead, can reach a distance up to a few tens of meters and a bitrate of a few kbps [25]: their main advantage is the possibility to cross the water-to-air boundary, but their high transmission power may affect marine life.

Able to cover the same distance, but also to provide a higher rate of a few Mbps, optical modems are currently the preferred communication devices for underwater broadband short-range links [28]: while light emitting diodes based transmitters can provide a rate of a few Mbps at a range of tens of meters, laser-based systems can achieve a higher distance and rate, but transmitter and receiver have to be perfectly aligned. Currently, acoustic modems are the only devices able to establish long underwater links, up to a distance of tens of kilometers [3]. Despite their low bitrate imposed by the low bandwidth available in the acoustic channel, they are the mostly used communication technologies, with several industrial and research devices being developed in the last decades: for this reason this paper reviews the state of art of underwater acoustic communication systems. The four aforementioned communication technologies are summarized in Figure 3, where we can clearly observe that optical communication outperforms all other technologies for short range links, while acoustic is the only technology able to support long range communication. Still, the fact that magneto inductive and RF are not affected by turbidity, multipath, sunlight and shipping noise, make them valuable alternatives when the channel conditions are not favorable for acoustic and optical communication.

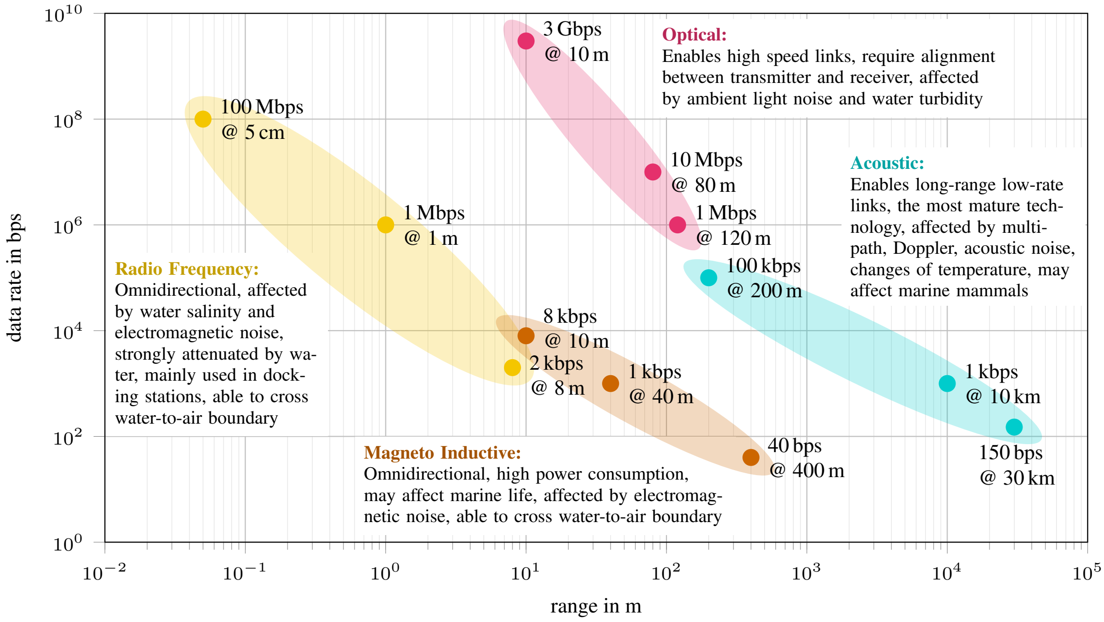


Figure 3. Comparison between underwater communication technologies (based on [27]).

2.2. Acoustic Modems for Offshore Applications

Underwater sensor networks are typically used in military and offshore applications. Their main requirement is to provide the coverage of a wide area where an asset needs to be maintained under control. In military scenarios, for instance, the goal is to perform surveillance of a strategic site, usually located near the coasts, identifying whether enemies are approaching that area. In Oil and Gas applications, instead, AUVs are often used to monitor pipelines and Oil stations: a network of submerged nodes helps maintaining the control of the vehicles for the whole mission duration.

Depending on the expected conditions and the user needs, there is a wide set of acoustic modems for offshore and military applications in the market, that can be employed in a variety of specific scenarios.

For example, to achieve a communication range of more than 4 km, modems with a carrier frequency below 12 kHz are usually used: in this category we can mention the Benthos ATM 960 modem operating in the low frequency (LF) band [3], the EvoLogics S2C 7/17 [1] modem, and the Develogic HAM node [2]. The transducers of most of these devices can be customized to the geometry of the channel and also the modem bitrate can be adapted accordingly. For this reason, all LF modems can achieve a communication rate up to a few kilobits per second in a vertical link in deep water, where the multipath is negligible, while in a horizontal link in very shallow water they can reach a maximum rate of few hundreds of bits per second. These modems are the mostly used in military applications, where nodes are often organized in barrier to identify if an intruder is approaching a protected area, and the goal is to cover the widest area with the minimum number of nodes [29]. Also, the first version of the NATO JANUS standard [30], that enables interoperability between modems of different manufacturers, focuses on LF acoustic communications, and so does the first version of the NATO underwater telephone and telegraph [31].

medium frequency (MF) modems, instead, are the most used for communication ranges from 1 to 3 km, as they can cover this range by providing a bitrate higher than LF modems. In this paper, we classify as MF all modems with a carrier frequency between 20 and 35 kHz. All the aforementioned manufacturers that produce LF devices also develop MF acoustic modems. In addition to them, other companies also supply commercial off-the-shelf products in this range, such as the Popoto Modem [32], the Applicon Seamodem [33], the Sonardyne 6G [34], the DSPComm Aquacomm Gen2 [15], the SubNero [35] and the Blueprint Subsea [36] acoustic modem. These modems are the most used onboard AUVs and inspection class ROVs, as they are smaller and lighter than LF modems, significantly simplifying their integration in unmanned vehicles, still providing a communication range of a few kilometers. In addition, using ultrasounds for the transmission and the reception, they are less affected by acoustic noise caused by vessel propellers [37]. For this reason, in the new military scenarios, multimodal networks composed of both LF and MF acoustic modems are often considered [38,39], where the MF modem is used to communicate between nodes in the same barrier and with AUVs, and the LF communication system is used to communicate between nodes in different barriers. Various manufacturers [31,40] and research institutes [41,42] develop acoustic modems in the LF and MF band for their national defence, confirming the interest of the Navy in these devices.

In the context of offshore and military applications, high frequency (HF) acoustic modems (with a carrier frequency higher than 35 kHz) are rarely used, due to their short range, that is typically below 500 m. Although their high throughput (of about a few tens of kbps) can support interesting applications, such as quasi-realtime underwater low-quality video streaming [43,44], their short range makes their use very limited in coast surveillance scenario or deep water offshore applications. In fact, in this context they can only be used onboard AUVs that use MF or LF modems to coordinate their mission, and switch to HF when approaching a submerged node or a docking station to download a large quantity of data in a short time. Despite this data gathering (or data muling) application is of interest in these scenarios, there is a factor that need to be considered before deciding to adopt HF communication in this context [27]. Indeed, if an AUV approaches another submerged node, also other communication systems may be used. Specifically, for distances below 50 m optical and electromagnetic modems can provide a very high throughput (up to a few Mbps) and are often preferred to HF modems [27]. A few companies supply HF acoustic modems for offshore applications. LinkQuest UWM220 [45] uses a carrier frequency of 70 kHz to achieve a datarate up to 19 kbps at a range of up to 1 km. Evologics [1] provides two high-power HF modems, one for horizontal and one for vertical communication, with a carrier frequency between 50 kHz and 60 kHz, able to transmit up to 30 kbps at a range of 1 km. They also supply a very high speed modem that uses a carrier frequency of 150 kHz and can transmit with a datarate of 60 kbps up to a range of 300 m. The latter has been used during an academic study in [43] to transmit a low quality video stream in quasi realtime. Other studies performed by Universities focus on HF acoustic communication. The SEANet modem [46], for instance, is designed to achieve a bitrate of more than 500 kbps at a range of a few tens of meters, using a carrier frequency of 500 kHz and a bandwidth of 600 kHz. The authors in [44] developed a multiple-input multiple-output (MIMO) acoustic modem able live stream a 200 kbps video acquired with a BlueROV to the operator, using the 1–180 kHz band. The modem is designed to transmit up to a distance of a few tens of meters. Finally, the Hermes modem [47] can achieve a distance of 100 m and a throughput of 80 kbps, using a frequency band from 260 kHz to 380 kHz.

2.3. Low-Cost Acoustic Modems

In the LF and MF domain, some universities and civil research institutes developed low-cost low-power modems for medium and short range (few hundreds of meters) low-rate (few hundreds of bits per second) UIoT applications [48–52], by employing low-cost narrowband transducers.

The design of one of the first low-cost acoustic modem is presented in [48], where all data processing was computed with a PC, and the authors used a simple PC microphone as a receiver and regular PC speakers as transmitter. They waterproofed the components with elastic membranes and managed to transmit a 24 bps frequency shift keying (FSK) signal up to a distance of 17 m using the frequencies between 1000 Hz and 2000 Hz. Similarly, the authors in [49] developed an FSK modem performing all signal processing in a PC with GNU RADIO, and developing their own do-it-yourself hydrophone composed of eight car-audio piezoelectric-tweeters (with the cost of 0.50 EUR each) waterproofed with a plastic container filled with vegetable oil. They managed to transmit with a rate of 100 to 500 bps over a distance of up to 6 m. A very small LF modem specifically developed for micro AUVs is presented in [53]. This modem uses direct sequence spread spectrum (DSSS) modulation with a central frequency of 12.5 kHz and a bandwidth of 3 kHz, obtaining a bitrate of 55 bps up to a distance of 200 m.

In the FPGA-based acoustic modem developed by University of California San Diego (UCSD) [51], the authors managed to avoid purchasing expensive underwater transducers by encapsulating in a potting compound a simple and low-cost piezoelectric transducer. They achieved a bitrate of 200 bps up to a range of 350 m transmitting in the 32–38 kHz band with a transmission power of 40 W. Although this modem uses a high power transmitter, its design inspired more recent works where other scientists developed their own underwater transducer. In [50], for instance, they introduce the concept of a surface receiver consisting of a hydrophone plugged into a standard sound card (with sampling frequency of 44.1 kHz or 48 kHz) of a mobile device such as a smart phone or tablet. They prove the possibility to transmit up to a range of 100 m transmitting with very low power and with a bitrate between 25 and 375 bps in the 8–16 kHz band, using a very low-cost hydrophone and chirp waveform. Using a similar waveform, the low-power Nanomodem [52] (and its newer version number 3 [54]) developed by the University of Newcastle, operates in the 24–28 kHz band, achieving a datarate of 40 bps within a surprising range of 2 km, despite the very low transmission power (168 dB re 1 μPa @ 1 m). The same research group also developed the Seatrac miniature acoustic modem [55] and USBL, that uses DSSS and operates in the ultrasonic 24–32 kHz band, achieving a throughput up to 1.4 kbps at a range of 1.5 km, with a transmission power of 176 dB re 1 μPa @ 1 m. It is designed to support communication and positioning between divers and ROVs and, despite it is a more complex system and uses a transmission power higher than the other modems discussed so far, its deserves to be mentioned in this context as its licence has been provided not only to Blueprint Subsea, that commercializes the USBL as it is, but also to Succorfish, that developed the SC4X portable integrated acoustic, iridium and GSM diver communications system [56], a low-power modem used to enable diver to diver and diver to surface communication with a datarate of 463 bps. The acoustic module installed in the latter does not uses USBL and has a maximum transmission power of only 168 dB re 1 μPa @ 1 m (like the Nanomodem), with significant reduction in development costs.

A low-cost modem developed by the Tianjin and the Guilin Universities, China, based on the embedded system STM32H743 that uses single and multi carrier MFSK schemes has been presented in [57]. The modem can achieve a distance of 5 km with a bitrate of 125 bps, and of 2.5 km with a bitrate of 1 kbps, and operates in the 20–30 kHz band.

Some commercial low-cost LF and MF acoustic modems (with a price of less than 2 kEUR) are also available off-the-shelf. For instance, the modem launched by DSP-

Comm [15] costs about 1 kEUR, uses the 16–30 kHz band, has a maximum transmission rate of 100 bps, and a nominal range of 500 m. With the same range, the Micron Data Modem developed by Tritech [13] is a low power compact modem with a maximum data rate of 40 bps and operates in the 20–28 kHz band. Its transmission power is up to 169 dB re 1 μPa @ 1 m and weighs less than 250 g. This modem is a commercial version of the aforementioned Nanomodem [52] designed by the Newcastle University, that gave Tritech its licence to produce the Micron Modem. DiveNET, a company that mainly produces communication and localization equipment for divers, supplies Sealink [58], an affordable and low power acoustic modem that provides either a range up to 8 km at a datarate of 80 bps using the 5–15 kHz band (models C and S) or, with a more compact design and a lower transmission power, a range of 1 km at a datarate of 78 bps using the 15–30 kHz band. Subnero [35], in addition to its high power and high depth-rated devices for industrial applications, it supplies a research edition software-defined-modem (WNC-M25MRS3) operating in the 20–32 kHz band and able to transmit up to 15 kbps at a maximum range of 1 km, with a source level of 175 dB re 1 μPa @ 1 m. Based on our knowledge, its price exceeds the one of the other low-cost commercial modems listed in this section, but is still less than half the cost of the modems used in offshore applications. Popoto Modem [32], in addition to solutions for offshore applications, also provides a series of low-rated and low-power modems with an affordable price of less than 2500 EUR. These modems use the 20–40 kHz band and achieve datarates up to 10 kbps at a typical range between 1 and 2 km. The AppliCon SeaModem [33] is commercially available as well: the modem uses FSK to transmit up to 2 kbps within a range up to 400 m. The modem uses a central frequency of 30 kHz and a bandwidth of 10 kHz.

Also, affordable HF acoustic modems have been developed by both research institutes [12,16,59,60] and companies [11,14].

The very small ahoi modem [12] has a total component costs of less than 600 EUR, including an off-the-shelf transducer (400 EUR), microprocessor and the transceiver board developed in house (200 EUR). It uses a very low transmission power of 160 dB re 1 μPa @ 1 m and the frequency band of 50 kHz to 75 kHz, achieving a throughput of 260 bps (default net rate, that can be increased up to 4.7 kbps in good channel conditions) and a range up to 200 m in very shallow water, thanks to a robust frequency hopping (FH) FSK modulation. The recently-developed MODA modem [60] uses all off-the-shelf hardware components, including a Raspberry PI4 as a processing unit, a high quality 192 kHz audio DAQ Raspberry HAT, an audio amplifier for transmission, an hydrophone preamplifier in reception and two transducers, one for transmitting and one for receiving. The cost of all the components is 1000 EUR per modem: this price can be lowered significantly (of about 400 EUR) if a tx/rx switch is used instead of a second transducer. Optionally, the modem is designed to perform one way time travel ranging by relying in precise clocks such as oven-controlled crystal oscillator, that are more affordable than atomic clocks. The modem uses a carrier frequency of 50 kHz, a bandwidth of 20 kHz, and it is still under evaluation. For this reason the performance figures are not available at the moment: preliminary results have shown that it can perform reliable transmissions with a bitrate of 1 kbps at a distance of 80 m.

The low-cost modem recently developed by the Xiamen University [61], China, operates in the 35–45 kHz frequency band, and is able to achieve 500 m with a bitrate of a few hundred of bits per second using FH-MFSK. The total cost of components is approximately 500 EUR and the maximum power consumption, when transmitting, less than 6 W. The micro-modem developed by the Gangneung-Wonju National University (South Korea) has a maximum consuming power of 8 W and transmits an BPSK signal using a frequency of 70 kHz [62], reaching a maximum distance of a few hundred meters and a transmission rate that ranges between 200 bps and 5 kbps. The ITACA modem [16] provides transmission of digital data using coherent-FSK at rates of 1 kbps with an 85 kHz carrier frequency: the authors managed to transmit up to 240 m with a transmission power consumption of only 0.1 W. It uses a precise real-time-clock to perform coherent demodulation and to use a TDMA MAC scheme. It uses low-cost transducers (with a cost of about 100 EUR each) usually employed in low-cost echosounder applications, hence significantly reducing the hardware cost.

Using a carrier frequency of 40 kHz, the FSK ultrasonic modem presented in [59] uses a very low-cost waterproof ultrasonic transducer typically used in the automotive industry for measuring the distance from the car and the closest obstacle. All processing is performed with an Arduino, and from a pool test the authors managed to perform error-free transmissions with a bitrate of 1.2 kbps up to a range of 1.5 m. The researchers from the Florida Altantic University (FAU) [63] recently developed a low-cost HF modem prototype with a transmission power of 5 W that, using FH-FSK is able to reach 50 m with a bitrate of 100 bps in the 100–150 kHz frequency band.

Two commercial HF acoustic modems are avaliable off-the-shelf [11,14]. The low-cost Desert Star SAM-1 modem [14] uses either the 34–48 kHz band or the 65–75 kHz band, has a bitrate of a few tens of bits per second and a typical range of 250 m. Compared to the other low-cost acoustic modems described so far, it has a higher transmission power (up to 189 dB re 1 µPa @ 1 m) and uses pulse position modulation (PPM) instead of spread spectrum techniques such as DSS or chirp-based modulations. Waterlinked, instead, supplies the M64 acoustic modem, able to achieve a range up to 200 m and a bitrate of 64 bps. This low-power modem can be easily integrated in a BlueROV, and operates in the frequencies between 31 and 250 kHz.

The most representative low-cost underwater acoustic modems discussed in this section are summarized in Figure 4 and Table 1.

Table 1. Summary of state-of-the-art of affordable acoustic modems.

	Manufacturer and Model	Developer	Max Range	Bit Rate	Freq. Range
LF	DiveNET: Sealink {C,S} [58]	commercial	8 km	80 bps	5–15 kHz
	Modem prototype for µAUVs [53]	research	200 m	55 bps	11–14 kHz
MF	UCSD prototype [51]	research	350 m	200 bps	32–38 kHz
	Nanomodem prototype [52,54]	research	2 km	40 bps	24–28 kHz
	Tritech Micron Data Modem [13]	commercial	2 km	40 bps	24–28 kHz
	Tianjin + Guilin modem [57]	research	{2.5–5} km	{0.125–1} kbps	20–30 kHz
	Applicon Seamodem [33]	commercial	100s of m	{0.75, 2} kbps	25–35 kHz
	DSPComm Aquacomm Gen2 [15]	commercial	8 km	{0.1, 1} kbps	16–30 kHz
	DiveNET: Sealink M [58]	commercial	1 km	78 bps	15–30 kHz
	Subnero research modem [35]	commercial	1 km	15 kbps	20–32 kHz
	Popoto low power modem [32]	commercial	1 km	10 kbps	20–40 kHz
HF	ahoi modem [12]	research	200 m	260 bps	50–75 kHz
	ITACA modem prototype [16]	research	200 m	200 bps	85–200 kHz
	Waterlinked M64 [11]	commercial	200 m	64 bps	31–250 kHz
	Desert Star SAM-1 [14]	commercial	240 m	1 kbps	34–48 kHz or 65–75 kHz
	MODA modem [60]	research	80 m	1 kbps	50–70 kHz
	Xiamen Uni. modem [61]	research	500 m	200–300 bps	35–45 kHz
	South Korea Univ. modem [62]	research	{100–300} m	{0.2–5} kbps	70 kHz
	FAU modem [63]	research	50 m	100 bps	100–150 kHz

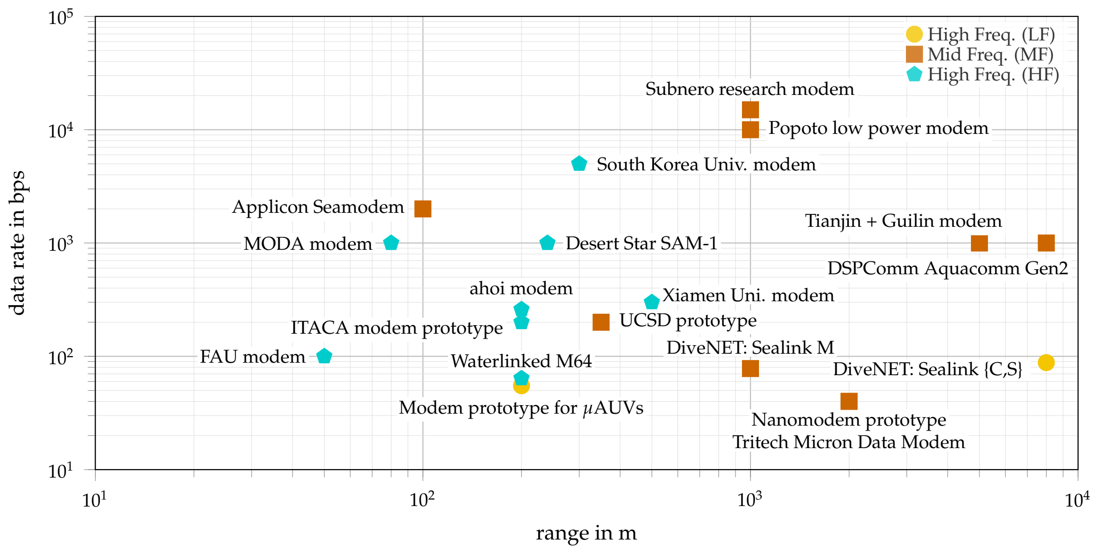


Figure 4. Range vs. data rate of recent low-cost acoustic underwater modems.

3. Underwater Acoustic Positioning Systems

In this section, we introduce different underwater positioning systems. Positioning is a requirement for vehicle navigation and therefore mandatory for autonomous missions. In addition, underwater positioning can be used to track submerged equipment or to localize sensor nodes in an underwater wireless sensor network (UWSN). At first, we discuss different types of underwater positioning systems and focus on acoustic range-based positioning systems. Afterwards, we review acoustic positioning systems for offshore applications. At last, we discuss the requirements for low-cost positioning systems and review state-of-the-art systems.

3.1. Introduction to Underwater Positioning Systems

Underwater positioning is a challenging task. Due to the high damping of the electromagnetic waves, widely used over-water systems, e.g., global navigation satellite system (GNSS), are not applicable. Usually, underwater positioning systems can be categorized into four methods [22–24]: dead-reckoning, geophysical, optical, and acoustic. Figure 5 summarizes the four methods and lists advantages and disadvantages. Dead-reckoning or inertial navigation tries to estimate the vehicle position based on the integration of the velocity over time. The velocity can be measured with a Doppler velocity log (DVL) or inertial measurement unit (IMU) (consists of accelerometers, gyroscopes, and, usually, magnetometers). This method does not require external infrastructure, such as reference points. However, due to the integration of signals with measurement errors, the error of inertial navigation increases over time. In particular, systems with accelerometers are susceptible to drifts based on the double integration computed by the system (the first to calculate the velocity and the second for the position) [64]. An inertial navigation system (INS) fuses the IMU data streams, for example with a Kalman filter or an extended Kalman filter (EKF), and estimates position and rotation. Geophysical methods are gravity or geomagnetic navigation, which use very-small position-depended changes of the gravity or the magnetic field to estimate the vehicle position [23]. Also other geophysical parameters, such as bathymetry, can be used. However, an a-priori knowledge of the geophysical parameter, e.g., a geophysical map, is required to match the measurement with possible results. Optical systems can use light detectors or cameras to find markers, e.g., [65]. Another method is to use camera-based simultaneous location and mapping (SLAM). SLAM is used in scenarios where a vehicle is placed at an unknown location in an unknown environment. The algorithm builds a map and determines the vehicle position inside this map [66]. However, optical systems require a high visibility as well as low turbidity and illumination. Acoustic systems include sound navigation and ranging (SONAR) and acoustic range measurements.

SONAR sensors can be used to replace cameras in SLAM algorithms [67] to overcome the problems of cameras in high turbidity or low light scenarios.

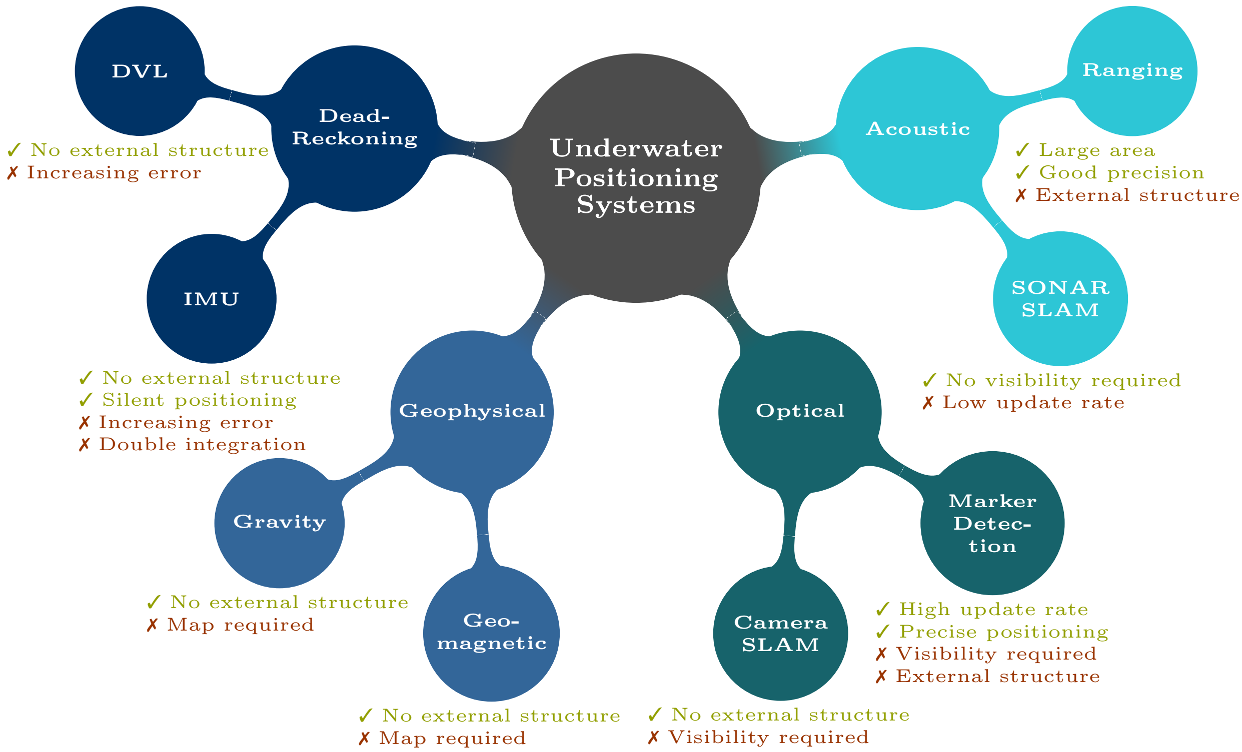
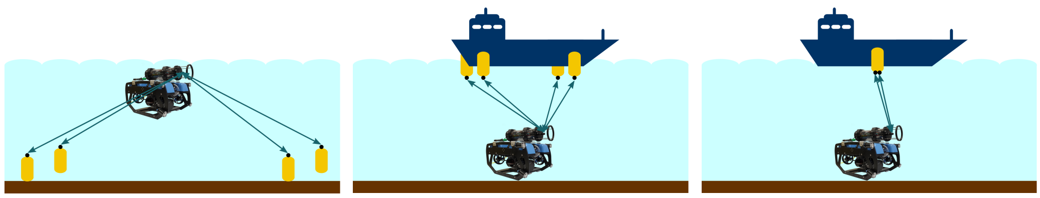


Figure 5. Comparison between different underwater positioning systems based on [22–24]. Abbreviations: Doppler velocity log (DVL), inertial measurement unit (IMU), simultaneous location and mapping (SLAM), sound navigation and ranging (SONAR).

In the following sections, systems based on acoustic range or relative range difference measurements are discussed. In this paper, the reference stations are named anchors and the agent is the target with unknown position. The agent could be a vehicle, submerged equipment, or a sensor node. Typical configurations are shown in Figure 6. In all cases, distance measurements to external reference stations are used to calculate the agent's position. Different systems can be classified by the anchors' position. Long baseline (LBL) systems cover a wide area and the anchors are mounted on fixed structures in the underwater environment or under buoys. Short baseline (SBL) systems have smaller distances between anchors, typically they are mounted at the outer edges of a ship hull or under small buoys. In an ultra short baseline (USBL) system, multiple hydrophones (or receivers) are installed in a single device located in a well known position, e.g., under a ship. The typical distances between anchors ranges from 50 m to more than 2000 m for LBL systems and from 20 m to 50 m for SBL systems [68]. Normally, acoustic ranging systems measure the agent's position in a local coordinate frame: additional GNSS receivers attached to the anchors allows a conversion into global coordinate frames. The distance between anchor and agent can be measured with the time of flight (TOF) or received signal strength (RSS) of the acoustic wave. Due to the strong multipath propagation and acoustic background noise, TOF is more accurate and the preferred option [69].

Most of the systems are based on one way ranging (OWR) or two way ranging (TWR). In both cases, the TOF of the acoustic wave between agent and anchor or difference between time of arrivals (TOAs) are measured. With the knowledge of the speed of sound (around 1500 m/s), the distance can be calculated. In OWR systems, the wave travels once (from the agent to the anchors or the other way around) and in TWR systems twice. OWR requires a synchronization between agent and anchors to calculate the TOF based on the TOA, which could be challenging as a result of clock drifts between different components [70].

Using time difference of arrival (TDOA) a synchronization of the agent is not required with the cost an additional anchor [71]. In most of the cases, e.g., [23], the agent periodically transmits acoustic beacon signals to the anchors. This configuration is recently named with *beacon* (i.e., the transmitting device attached to the agent) and *hydrophones* (i.e., the anchors, which receive acoustic beacon signals). However, it is also possible to invert the system. The anchors transmit periodically acoustic beacon packets to the agent. The first system enables an external positioning of the agent at the base station, e.g., for a ROV operator to know the ROV's position. However, for autonomous driving, the base station has to transmit the position back to the agent in this configuration, for example with an acoustic modem. The second system has a higher complexity, because the receiver on the agent has to distinguish between different beacon signals, which may also interfere, but allows the self-localization of the agent. TWR does not require a synchronization between agent and anchors. For example, the agent initializes the TWR measurement and transmits an acoustic signal to the first anchor, which directly responds with an acoustic signal. Based on the time difference between transmitted and received acoustic signals, the agent computes the distance from the first anchor. Afterwards, the agent repeats the same procedure with all the other anchors in sequence [12]. Opposed to OWR, TWR has a lower update rate due to sequential range measurements and the doubled travel time. If the agent and anchors are perfectly synchronized, instead, OWR techniques can be applied as the TOF can be computed without the need of a response and at the same time. In all cases, the agent node moves during the range estimation and induces ranging errors and Doppler shifts. Due to the low propagation speed of the acoustic wave, this effect is more relevant compared to over-water localization systems based on the electromagnetic wave. In [72] agent movements during acoustic range measurements are discussed and simulated, while the algorithm presented in [73] includes mobility in the ranging operation. Furthermore, Doppler shifts effect the underlaying acoustic communication scheme. Without Doppler removal the reception rate and therefore the position update rate decreases. Swarms of micro AUVs [74] are recent research topic: this application requires the positioning system to scale for multiple agents. If the agent transmits acoustic signals, a media access control (MAC) protocol is required and the update rate is reduced. From this point of view, an OWR system with silent agents (the agents receive only) has a better scalability. This scenario equals GNSS with transmitting anchors (satellites) and silent agents (GNSS receivers). Alternatively, agents in a swarm can serve as anchors after a successful self-localization (via OWR or TWR) and share their believed position to other agents.



(**a**) LBL system (**b**) SBL system (**c**) USBL system

Figure 6. Acoustic underwater localization systems. The agent (in these figures a BlueROV2) carries a node to localize the agent with distance measurements to anchors (in yellow) at fixed positions. LBL: 50–2000 m between anchors. SBL: 20–50 m between anchors. USBL: single device. Abbreviations: long baseline (LBL), short baseline (SBL), ultra short baseline (USBL).

Although several other different methods exist (e.g., the authors in [75] present a silent positioning with OWR and without previous synchronized clocks between the nodes), the methods discussed in the following Sections 3.2 and 3.3 are classified according to Table 2, that summarizes acoustic ranging methods typically used in underwater deployments.

Opposed to the previously discussed and only range-based LBL and SBL systems, USBL systems calculate the angle of arrival and the range. An USBL receiver consists of an hydrophone array to measure the phase difference or TDOA of the signals at the hydrophones [68]. Based on that, the USBL receiver estimates the angle of arrival and therefore the position in combination with a single range measurement. The small size of the hydrophone array allows an integration of the system in a single device. Normally, an USBL system is composed of two devices, the USBL transducer array and a transponder. In most of the cases, the transponder is an acoustic modem used to transmit the acoustic signals that are received by the USBL transducer array. Usually, the USBL transducer array is mounted in a well-known position, e.g., under a boat. The agent carries the transponder and can be localized with the USBL transducer array. Many systems can localize multiple transponders. For self-localization, the USBL transducer array is attached to the agent and the transponder is the anchor of the system.

Table 2. Summary of typical ranging methods between agent (for example the vehicle) and anchors (reference points). The category *simplex transmission* refers to devices that only transmit or receive. For example, the agent sends broadcast signals to the anchors. This reduces the amount of hardware compared to an application where agent and anchors have to transmit and to receive. Abbreviations: one way ranging (OWR), two way ranging (TWR), time of arrival (TOA), time difference of arrival (TDOA), transmitter (TX), receiver (RX).

			System Possibilities					System Requirements		
Method	**Agent**	**Anchors**	**Self-Localization**	**Silent Positioning**	**High Update Rate**	**Simple Scalability**	**Resilience Clock Drifts**	**No Sync. Anchors**	**No Sync. Agent Anchors**	**Simplex Transmission**
OWR, TOA	TX	RX	-	-	✓	-	-	(✓)	✓	✓
OWR, TDOA	TX	RX	-	-	✓	-	-	-	-	✓
OWR, TOA	RX	TX	✓	✓	✓	✓	-	(✓)	✓	✓
OWR, TDOA	RX	TX	✓	✓	✓	✓	-	-	-	✓
TWR, TOA	TX/RX	RX/TX	✓	-	-	-	✓	✓	✓	-

3.2. Acoustic Positioning for Offshore Applications

In the last decades, many underwater acoustic localization systems were developed by industry and research institutes. Many manufacturers from Section 2.2 also produce LBL and SBL systems. For example, the EvoLogics S2C R product line [1], the Develogic HAM node [2], Benthos ATM line [3], the Popoto Modem [32], Applicon Seamodem [33], Sonardyne 6G [34], and SubNero [35] provide range measurements between two modems. Based on the range measurements, LBL and SBL systems can be established. Among the others, the EvoLogics S2C R product line operates in kilometre ranges and has an accuracy of up to 0.015 m. The authors in [76] used TWR measurements with Evologics modems for localization of a single small AUV. They equipped two surfaced AUVs with global positioning system (GPS) and acoustic modems and ran the localization and navigation algorithm on the submerged AUV. In their evaluation, the small swarm traveled a route of 100 m in a V-shaped formation. To overcome the drawbacks of TWR, in [77,78] chip scale atomic clocks (CSACs) were connected to the Seamodem in the first and to EvoLogic modem in the second paper to archive OWR-based positioning of AUVs. The price for a single CSAC is more than 5000EUR. The system in [77] was evaluated in a static scenario with a few range measurements between two nodes with 479 m distance. In their setup, TWR had a standard deviation of 0.28 m and OWR 0.11 m. Opposed to that, in [78] a formation of two autonomous surface vehicles (ASVs) with real time kinematic global positioning system (RTK-GPS) and an AUV travelled a 30 min long track within an area of 100 m $\times$ 50 m. During the evaluation, the AUV localized himself with respect to the ASVs with a standard deviation of 0.09 m.

Many research projects [79–82] examined underwater acoustic positioning based on LBL and SBL systems. The authors in [79] used surface buoys with GPS receivers and submerged hydrophones under the buoys. The hydrophones receive acoustic pulses from the synchronized pinger (OWR system) and compute the TOA. Moreover, in [80] buoys were also used in combination with OWR. However, the system was not evaluated in their paper. WHOI modems [82] were used in [81] for the navigation of a small AUV and an underwater glider. The anchors were mounted on mobile surface vehicles. The system operated in the kilometer range and had position errors up to 25 m.

USBL systems requires less infrastructure and are thus easier to deploy. For example, the authors in [83] developed a USBL system based on TWR with DSSS modulated signals. The system was evaluated in [84] in combination an INS. Their tightly coupled USBL/INS had root mean square (RMS) errors between 1.04 m (circa 35 m $\times$ 40 m $\times$ 10 m operational volume w. r. t. to the USBL reference frame) and 2.48 m (circa 100 m $\times$ 150 m $\times$ 50 m). The authors in [85] used an USBL to improve the dead-reckoning (EKF with IMU and propeller thrust) capabilities of an AUV. Every USBL position update, the error between reference GPS and estimated position decreased.

The industry developed many USBL systems during the last decade, e.g., Evologics produces different USBL systems with ranges between 1 km to 10 km with 0.01 m slant range accuracy (accuracy of the distance measurement between transducer array and transponder) and 0.1° bearing resolution (resolution of the angle of arrival measurement at the transducer array) [86]. Furthermore, the Tritech MicronNav 200 [87] is a USBL system in the frequency band from 20 kHz to 28 kHz with 500 m horizontal and 150 m vertical tracking range. The system has 0.2 m accuracy and is Doppler tolerant for relative velocities up 5 m/s. The Teledyne Benthos Trackit USBL [88] system has 1500 m tracking range with up to 0.5% slant range accuracy with a small bandwidth from 22 kHz to 27 kHz. Besides, iXblue has different USBL systems. The iXblue Gaps M7 [5] comes with 4 km range, up to 0.06% slant range accuracy, 3 m/s Doppler tolerance and operates in the 21.5–30.5 kHz. The largest range has the Sonardyne Ranger 2 USBL [89] with 11 km tracking range. The system has up to 0.04% slant range accuracy and operates in the 19–34 kHz or 14–19.5 kHz (required for full 11 km range) frequency band.

3.3. Low-Cost Acoustic Positioning Systems

Comparable to the low-cost acoustic modems in Section 2.3, low-cost acoustic positioning systems are a rising research topic. Based on the progress in micro AUV research fields, micro AUV and other low-cost underwater robots outgrow test tanks in universities and are deployed in real-world scenarios. Applicable positioning in test tanks, e.g., camera-based localization, do not operate in these scenarios. The previously discussed systems in Section 3.2 are too large and expensive for low-cost micro AUVs. Based on that, many papers have been published on that topic and several commercial positioning systems have been launched during the last years.

The Nanomodem [52] was used in [90] in a setup with three anchors in an area of circa 50 m $\times$ 50 m and a mobile small AUV. The authors used the Nanomodem for underwater communication and the TWR measurements were calculated on the network layer, based on the algorithm in [91]. However, due to the lack of a ground truth, the accuracy of the setup was not evaluated. In [92] the authors presented an OWR setup with a temperature compensated crystal oscillator in the micro AUV for the synchronization. The anchors used GPS receivers for time synchronization. The anchors transmitted periodical acoustic orthogonal frequency-division multiplexing (OFDM)-modulated beacons to the micro AUV. In their evaluation, in an area of circa 30 m $\times$ 15 m, the authors archived an trajectory RMS error of 1.66 m with a static and a moving anchor. The ahoi modem [12] was used in [93]. Four ahoi modems were deployed on jetties in an area of circa 70 m $\times$ 70 m. The manually controlled BlueROV2 initialized the TWR measurements for self-localization. During the evaluation, the BlueROV2 had a depth of circa 1.7 m and a mast with a GPS receiver was installed on top of the BlueROV2 for ground truth. A trajectory RMS error of

1.36 m, respectively 1.2 m circular error probable (CEP) were measured during the trials. However, the used GPS receiver had a position accuracy of 2.5 m CEP. The lack of an appropriate ground truth was solved in [94]. The authors used a RTK-GPS on a mast outside of the water and they measured a positioning error below 0.4 m in an area of circa 25 m × 25 m, with two ahoi modems and an EKF. In [95], an OWR system for a micro AUV is described. However, most of the paper described the concept, self-build transducers and simulations. In a short real-world evaluation, they made range measurements between a single transmitter and receiver with circa 1.5 m distance in order to test the hardware. Another promising approach is presented in [96]. The authors used acoustic backscatter communication [97] for TWR measurements. The anchors harvested energy from the received acoustic wave and respond via backscattering. This approach omits the presence of batteries or other external power sources at the anchors and make them suitable for long-term deployments. However, the research on that topic is at the beginning and the authors presented simulations and a short feasibility study with range measurements. WaterLinked Underwater GPS [98] is a commercial SBL system with four anchors and up to 300 m range. The 300 m range version starts at a price of circa 5000EUR. A locator is attached to a vehicle and transmits periodically beacon signals (typically at 200 kHz), which are received by the anchors (OWR system). All anchors are connected to a central processing unit outside the water and the position is calculated in this unit. In the case of autonomous driving, the position has to be transmitted to the vehicle, e.g., via tether or acoustic communication. However, this increases cost for an additional communication link and long latency in the case of acoustic communication. The system has a position update rate of 2 Hz, 0.2% accuracy of horizontal range, and 1% accuracy of vertical range. The locator is synchronized to the central processing unit via a connection cable, e.g., tether, or with GPS at the beginning of a mission. Due to clock-drifts the cable-free locator produces a drift of 0.17 m/h

USBL systems reduce the installation cost because only a single anchor is required. The authors in [99] installed a hydrophone array in the front of a small AUV (Bluefin SandShark). The acoustic beacon (anchor) transmitted periodically up-chirps with 20 ms symbol duration and in the bandwidth from 7 to 9 kHz via an underwater loudspeaker. The periodic transmission was triggered with a GPS receiver. On the other side, the AUV had a CSAC, which was synchronized to the transmitter at the begin of the mission. The system used OWR with a silent agent and offered multi-vehicle positioning at the same time without additional costs, e.g., anchors or acoustic transmissions. The data processing was running on a Raspberry Pi 3 inside the AUV. Furthermore, the authors used a particle filter and factor graph smoothing to calculate the position based on range and angular measurements. However, due to the absence of a ground truth, the authors measured the difference of the underwater position and GPS position when the AUV surfaces. The evaluation took place in an area of circa 140 m × 100 m and the authors measured differences between 2.9 m and 10.4 m (6.4 m mean during all experiments). The Blueprint Subsea Seatrac USBL is presented in a scientific paper [55] and is commercially available [6]. It uses 50 ms chirp symbols from 24–32 kHz for TWR. An ARM Cortex M4 is used for data processing and the USBL position can be fused with a depth sensor and an IMU. The system has an operational range of 1000 m and 0.1 m range resolution. Cerulean Sonar ROV Locator Bundle Mark II [100] and Mark III [101] have a range of 500 m and 0.1 m slant range resolution. Both systems have 1 Hz update rate and an IMU included. Mark II uses OWR for range estimation at 25 kHz. At the beginning of each mission, the high precision crystal oscillators are synchronized with a GPS signal. Clock drift results in 0.5 m/h slant range error accumulation. Opposed to that, Mark III is a TWR-based system at 25 kHz and 43 kHz to eliminate clock drifts. However, Mark III requires transceiver modules in anchor and agent opposed to Mark II, which has a transmitter on the agent and a receiver at the anchor. This is noticeable in the price, Mark II costs circa 2500EUR and Mark III 4000EUR. Sonardyne Micro-Ranger 2 USBL [4] has circa 1000 m range and

5% slant range accuracy. The system uses the bandwidth between 19–34 kHz and has 3 Hz position update rate.

Table 3, Figure 7 summarizes this section and gives a comparison of the discussed low-cost acoustic positioning systems. Finally, the number of low-cost localization systems is very limited. Most of the research projects focus on SBL and LBL systems. Opposed to that, many commercial low-cost devices are USBL systems. OWR has a faster update rate compared to TWR and requires less hardware. On the other hand, clock drifts produce large errors, e.g., 0.17 m/h or 0.5 m/h, in OWR-based systems. Furthermore, the lack of a ground truth is an important problem to compare different approaches and devices.

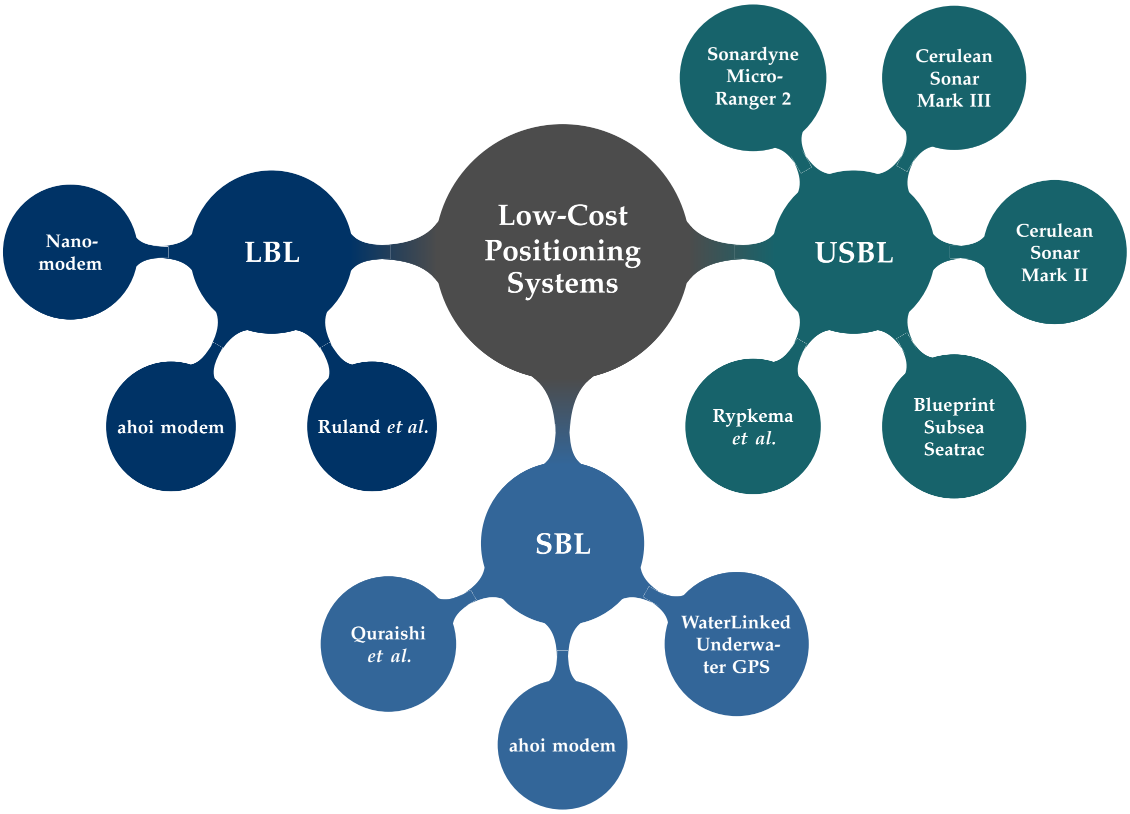


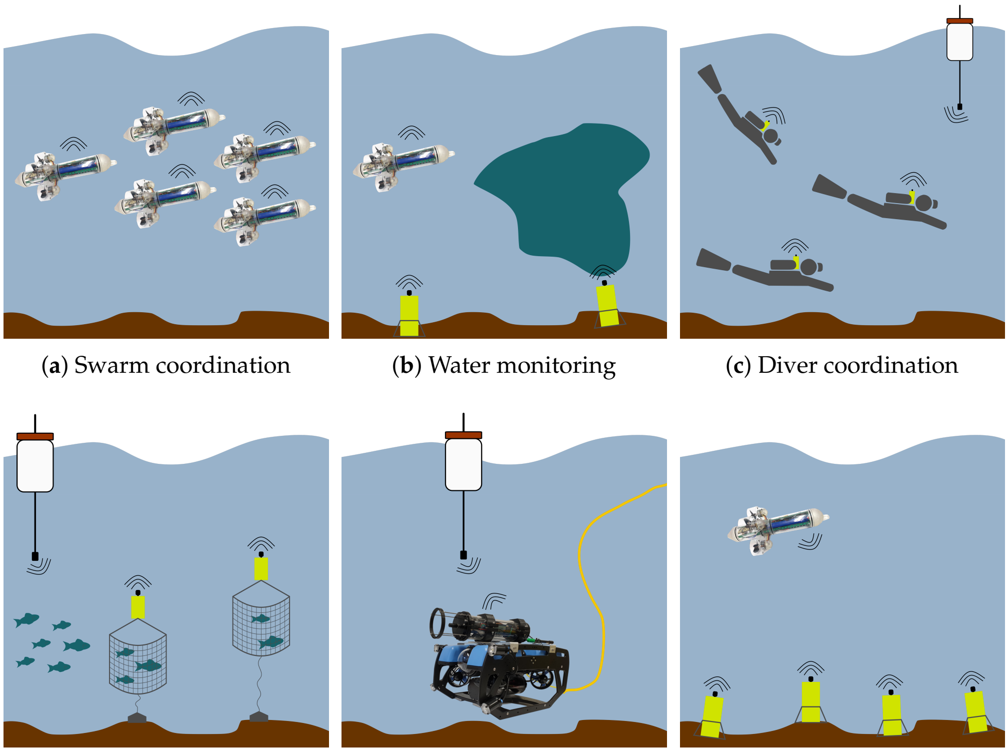
Figure 7. Summary of recent low-cost acoustic positioning systems. Abbreviations: long baseline (LBL), short baseline (SBL), ultra short baseline (USBL). (Ruland et al. [95], Quraishi et al. [92], Rypkema et al. [99]).

Table 3. Comparison of different low-cost acoustic positioning systems. Abbreviations: one way ranging (OWR), two way ranging (TWR), long baseline (LBL), short baseline (SBL), ultra short baseline (USBL), root mean square (RMS), circular error probable (CEP), real time kinematic (RTK), chip scale atomic clock (CSAC)

Device / Author	Algo.	Developer	Setup	Method	Area	Accuracy	Remarks
Nanomodem [52]	[90,91]	research	LBL/SBL	TWR	50 m × 50 m	lack of ground truth	TWR on network layer
Quraishi et al. [92]	[92]	research	SBL	OWR	30 m × 15 m	1.66 m RMS error	anchors transmit periodic (GNSS sync.) acoustic beacons
ahoi modem [12]	[93]	research	LBL	TWR	70 m × 70 m	1.36 m RMS error, 1.2 m CEP (GPS with 2.5 m CEP for ground truth)	BlueROV2 self-localization
ahoi modem [12]	[94]	research	SBL	TWR	25 m × 25 m	positioning error below 0.4 m (RTK-GPS)	two anchors in small buoys
Ruland et al. [95]	[95]	research	LBL	OWR	—	—	simulation, self-build transducers
Jang et al. [97]	[96]	research	—	TWR	—	—	backscatter communication feasibility study
WaterLinked Underwater GPS [98]	—	commercial	SBL	OWR	300 m × 300 m	0.2% horizontal, 1% vertical	synchronization via cable or GPS at the beginning of a mission (0.17 m/h drift).
Rypkema et al. [99]	[99]	research	USBL	TWR	140 m × 100 m	6.4 m mean error to GPS, when the AUV surfaces	anchors transmit periodic (GPS sync.) acoustic beacons. AUV is synchronized with a CSAC
Blueprint Subsea Seatrac [6]	[55]	research/ commercial	USBL	TWR	1000 m range	0.1 m range resolution	integrated IMU and depth sensor
Cerulean Sonar Mark II [100]	—	commercial	USBL	OWR	500 m range	0.1 m slant range resolution	0.5 m/h slant range error accumulation due to clock drifts
Cerulean Sonar Mark III [101]	—	commercial	USBL	TWR	500 m range	0.1 m slant range resolution	TWR to eliminate clock drifts
Sonardyne Micro-Ranger 2 USBL [4]	—	commercial	USBL	—	995 m range	5% slant range	typically no self-localization

4. Applications

Legacy applications of underwater acoustic networks and positioning systems include large-scale military and industrial operations. Among the most common military applications we can mention distributed coastal surveillance and monitoring, intelligence gathering, surveillance and reconnaissance (ISR), mine countermeasure (MCM), rapid environmental assessment (REA), and anti-submarine warfare systems (ASW) [39]. These applications involve the use of both sophisticated high-power acoustic modems and multiple AUVs, often cooperating in formation to perform coordinated tasks. Among the civil operations, instead, we can identify applications for Oil and Gas industry, such as wireless remote control for underwater vehicles, and pipeline inspection with autonomous vehicles [27], as well as applications for marine scientists and meteorologists performed with large scale observatories [102], such as coastal erosion and tsunami prevention systems. Also, in these legacy applications, where the deployment is performed in open sea, expensive unmanned vessels and acoustic modems and positioning systems are used. In Section 4.1 we will focus on new applications recently enabled with the development of low-cost underwater communication and positioning systems (Figure 8). In Table 4 we summarize the main applications of both legacy and low-cost acoustic modems and positioning systems.



(**a**) Swarm coordination (**b**) Water monitoring (**c**) Diver coordination

(**d**) Rope-less fish traps (**e**) ROV positioning (**f**) Data muling

Figure 8. Example applications for low-cost acoustic modems.

Table 4. Main applications of acoustic modems and positioning systems.

Legacy Acoustic Modems and Positioning	Low-Cost Acoustic Modems and Positioning
Oil and Gas pipes inspection with AUVs	Micro AUV swarm coordination
Ship to submarine communication and positioning	Internal water quality assessment
Tsunami prevention systems	Divers mission coordination
Coastal surveillance and monitoring	Rope-less crab and fish traps
Military applications (MCM, ASW, REA, ISR)	Low-cost ROV positioning
Data muling in open sea with large AUVs	Data muling in internal waters with low-cost AUVs
Work class ROV USBL and positioning	and ASVs

4.1. New Applications Enabled by Low-Cost Acoustic Modems and Positioning Systems

In this section, we both analyze the fact that some well-known but hard to develop applications became now feasible thanks to the availability of low-cost acoustic modems, and new applications that can provide a significant benefit to coastal areas. In the former group we find applications such as rope-less fish traps [103], low-cost ROV positioning [6], and divers mission coordination [56]. In the latter, we can certainly mention micro AUV swarm coordination [104], internal water quality assessment [105], and data muling with low-cost AUVs and ASVs [8].

Given the increasing interest in studying water quality and presence of pollutants in the water, as well as the effect of climate change to coastal areas and biodiversity, there is a rising demand for fixed and distributed subsea dense sensor deployments to measure the marine environment with high spatial and temporal resolution. For instance, in [106] it has been demonstrated that surface measurements are not enough to characterize the presence of pollutants in the water, given that plastic debris have been found up to a depth of several hundreds of meters. In [107], the authors envision the need of new low-cost and smart underwater sensor networks for seafloor monitoring: a key technology to develop these networks are resilient low-cost underwater modems. Moreover, the new European Biodiversity Strategy for 2030 is a comprehensive, ambitious, long-term plan for protecting nature and reversing the degradation of ecosystems, not only with immediate actions such as the creation of consortia to remove waste and debris from coastal areas, but also with the introduction of innovative solutions to monitor water parameters and pollutants. Low-cost underwater acoustic modems are a key enabling technology for these dense wireless sensor networks in the field of Internet of Underwater Things. In this context, many commercial and research organisations are exploring the use of miniature autonomous platforms for cost-effective oceanographic sensing. For example, H20 Robotics supplies a series of low-cost surface vehicle specifically tailored for acquiring water measurements [108], while ecoSUB Robotics [109] developed a line of small low-cost AUVs. In addition, the already mentioned BlueROV2 [9] is a small, low-cost, and open-source remotely operated vehicle that can perform some simple autonomous tasks and can be equipped with a series of modular sensors, including the acoustic modems manufactured by WaterLinked. In addition, the BlueROV is used by numerous research institutes as a platform for the development of localization and navigation algorithms, e.g., [110]. In the context of the EU H2020 subCULTron project, three types of robotic agents were developed to measure sensors data in a swarm formation. Specifically, newly-developed surface vehicles, AUVs and bottom nodes, all equipped with low-cost acoustic modems, were deployed to perform long-term marine monitoring and exploration in the Venice Lagoon [111]. A simple low-cost underwater robot for distributed sensing in coastal waters, named μFloat [112], has been developed the the University of Washington and PMEC. This floating trackable system is a drifting sensor package specifically tailored to be deployed in swarms to perform simultaneous, distributed measurements in energetic tidal currents. Both in subCULTron and μFloat projects underwater communication was enabled with the aforementioned low-cost acoustic modems developed by the Newcastle University. Similarly, in the RoboVaas project an underwater data collection use-case was demonstrated, using autonomous surface vessels (ASVs) and AUVs to retrieve data from a dense underwater acoustic sensor network [8], using the ahoi acoustic modems and the DESERT Underwater communication stack [113]. Although the discussed sensor platforms are not suited to open sea deployments, they can be used to monitor internal waters, such as rivers, lakes and lagoons, where the weather conditions are less challenging and assertion of water quality and inspection of the effect of climate changes on biodiversity is still very important.

In another RoboVaaS use case an ASV-carried low-cost ROV [114] was used to perform inspection of quay walls in the Port of Hamburg, characterized by shallow turbid water. In this context the use of low-cost underwater positioning systems, such as the underwater GPS supplied by WaterLinked, can provide a great help in the navigation of the ROV, given that the water turbidity makes the ROV video almost useless. Also, in areas with better visibility, where small AUVs can be used for camera-based fish monitoring [115], underwater localization is required to allow autonomous driving. An important problem that can be solved by using low-cost acoustic devices is the entanglement of marine mammals in crab trap lines set during the commercial crab fishery operations. This issue does no cause only the loss of traps for fishermen, but given that entangled traps and buoys interfere with the breathing of the mammal and restrict its feeding, can lead to the starvation of the animal. According to [103], tens of whales a year get entangled in crab trap lines in California: for this reason the Safe Passage Project aims to solve this problem developing an acoustically-activated rope-less gear system. Also, in this case the acoustic system must be very cheap, as the cost of each trap is a few hundreds of Euros. Lastly, low-cost low-power acoustic modems can be used for diver to diver, diver to ROV and diver to surface communication and positioning [6,56] in order to allow a better coordination during rescue missions and inspection of shipwrecks, as well as monitoring the health status of divers, hence limiting the risk of the human operators.

4.2. Current Challenges and Future Trends

The underwater acoustic channel is one of the most challenging transmission media and shows many variations depending on the environment [116,117], as the propagation in an open ocean vertical link significantly differs from the propagation experienced in a shallow water environment such as a port where the strong signal reflections make the multipath not negligible. Furthermore, the underwater acoustic channel changes over time [118], e.g., due to tidal and temperature changes or different ambient sounds. Measurement campaigns are time-consuming and expensive, hence many acoustic modems were tested in a single place over a short period. This makes the performance comparison between devices quite difficult, as it is not easy to replicate the same channel conditions in which other research groups made their tests. Long-term deployments and comparisons of different devices based on a larger number of measurements would help to assess the realistic modem performance and the comparison of measurement campaigns.

Another limiting factor is the lack of standardization that makes all modem manufacturers and research groups developing their own waveform, making interoperability between modems built by different groups almost impossible. In fact, also the JANUS NATO standard [30] focuses on first contact in LF acoustic networks, and also its next version focus on the LF and MF bands for military applications, leaving low-cost modems for civil application out of the discussion.

Despite the new availability of affordable acoustic modems, their use is still very limited to a few specific applications. One of the main reason for this is the lack of availability of low-cost buoys and bottom nodes equipped with batteries that are easy to deploy and maintain. For this reason some research institutes developed their own small buoys using waterproof containers mainly used for kayaking and other water sports, such as the one developed by the Hamburg University of Technology for the final RoboVaaS demonstration (https://www.youtube.com/watch?v=ZseCsm1kWmE&t=5s accessed on 21 December 2022). These nodes, that can be built with a cost of less than 150 EUR, are developed for testing purpose, and although they are sufficient for academic demonstrations, they cannot be used in long-term applications and are not commercially available. Still, their development require a non negligible human effort, making research groups investing time in building something that does not advance the state of the art, only for testing purposes. Conversely, commercial systems, such as the data buoys developed by Fondriest [119], are still too expensive to be used in a dense deployment, as they have a price starting from 1500 EUR, that is similar to the cost of H2Orbit, the low-cost surface vehicle recently developed by H20 robotics [108]. The lack of availability of these systems that should support low-cost experimentation and medium term deployments in controlled environment and internal waters, slows down the possibility to bring acoustic communication to the mainstream. Fortunately, some new companies started to sell less-expensive underwater components. For example, Blue Robotic offers watertight enclosures with different diameters and lengths. The tubes are available in acrylic plastic and aluminium and offer depth ratings between 70 m to 950 m. Blue Trail Engineering, instead, developed the low-cost Cobalt connectors and cables [120]. These connectors provide an affordable solution with three to eight pins and a 600 m depth rating. Moreover, the availability of affordable 3D printers allow research institutes to manufacture their components and connectors, further simplifying the prototyping phase. Presumably, more companies will launch new low-cost underwater components and platforms during the next years, as this is of interest for many research institutes. In addition to the ones already mentioned [9,108,109,111,112], we can cite the recent effort in this direction of the Abu Dhabi Technology Innovation Institute, that developed a first version of a low-cost robotic fish prototype for swarm missions named H-SURF [104].

The IoT for over-water applications is an active research field, with recent developments for the physical and network layer to support water quality measurements to study biodiversity, risk of floods in coastal cities and the effect of climate change [105]. Underwater acoustic communication can benefit from these new finding by adapting them for the underwater environment [121].

5. Summary and Conclusions

In this paper we presented a complete review of acoustic low-cost communication and localization systems, describing the main applications in which they can provide a significant benefit. By the authors best knowledge, it is the first paper which focuses on underwater low-cost acoustic systems and describes recent developments. Therefore, it is an important addition to existing review papers. It can be used for decision-making of research groups or product developers for new underwater projects.

After a quick overview of the different communication and positioning systems available based on electromagnetic, optical and acoustic waves, we decided to focus the paper on acoustic modems and positioning systems, that proved to be the most mature devices available to date. Although legacy acoustic modems, USBL, SBL, and LBL can provide very long range communication and precise positioning, their cost and power consumption are prohibitive for civil applications, indeed they are most used by military and Oil and Gas industries. Conversely, low-cost acoustic devices can support several civil applications, such as diver to diver communication, data retrieval from environmental sensors, and micro AUV swarms, with the trade-off of a lower bitrate, transmission range and precision. Although, in the past, these affordable devices were mainly developed by universities for research purposes, the recent development of low-cost AUVs and ROVs called for the need of these devices in the market, that have become finally available off the shelves. During the last years, many new low-cost underwater modems have been developed. On the other hand, the number of low-cost localization systems is still limited. There is a need for new systems, e.g., to enable autonomous driving of micro AUVs.

Furthermore, two of the main factors that limits their use in the main stream are (i) difficulty of deployment due to the lack of availability of low-cost buoys and bottom nodes equipped with batteries that are easy to deploy and maintain, and (ii) the lack of interoperability between modems built by different manufacturers due to the fact that a standard for low-cost underwater acoustic devices does no exist. Consequently, in order to take underwater sensor networks to the main stream, companies should focus their effort on the development of cheap and simple to handle floaters able to carry electronic equipment, making it available off-the shelf. Moreover, they should promote making the waveform publicly available. Universities and researchers, on the other hand, should provide the community simple and detailed how-to guides for their in-house developments, discuss and agree on a common modulation and coding scheme to enable interoperability between their prototypes, and disseminate their activities not only via scientific journals, but also organizing training events, such as tutorials, and summer and winter schools, where they can teach how to develop a low-cost simple software-defined modem, providing all participants an open-source platform that can be used both for basic experimentation and as a starting point for modem development.

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