Autonomous Underwater Vehicles: Instrumentation and Measurements

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Oceans exploration and inspection are a great challenge for the industry nowadays. The underwater instrumentation and measurements are improving due to the current technologies, or by development of new ones, to cover the demand of the new industry offshore. The Autonomous Underwater Vehicle (AUV), a subcategory of submarine, is used to perform subaquatic tasks. This vehicle provides advantages for underwater works, e.g., safety and reliability inspections, but it also offers limitations for sensors systems, monitoring and communications systems, autonomous operational endurances, propulsion systems or mapping designs, etc. The main scientific contributions of this paper are: a review of the state of art in novel and main instrumentation and measurement systems embedded in AUVs; an illustration of their future uses and development; and a synthesis of the main and current navigation, mapping and sampling technologies, together with different applications.

Introduction to Autonomous Underwater Vehicles

The oceans cover more than two-thirds of the planet. Only the equivalent of 15% of the oceans has been explored. The exploitation of the available ocean resources has been predominantly associated with fishing, tourism, and offshore oil and gas production, with limited activity ongoing in mining or other sectors with significant industrial and societal interest [1].

> *The sea is everything. It covers seven tenths of the terrestrial globe. Its breath is pure and healthy. It is an immense desert, where man is never lonely, for he feels life stirring on all sides. The sea is only the embodiment of a supernatural and wonderful existence. It is nothing but love and emotion; it is the Living Infinite.* —*Jules Verne*

The need appears in terms of submarine inspections in order to fix any industry offshore. To explore submarine environments presents many problems, e.g., the absence of human ability to breathe underwater and the water column pressure. There are many ways of conducting underwater inspections, from diving or snorkeling to the most sophisticated devices such as submarines or underwater vehicles [2].

There are various types of underwater vehicles, mainly divided in two categories: manned and unmanned systems. They can also be grouped into a number of different subclasses, e.g., unmanned systems towed by a ship. An AUV is a submerged system that contains its own power and is controlled by an onboard computer. Although these vehicles could be called remotely operated vehicles (ROV), unmanned underwater vehicles (UUV), submersible devices, or remote-controlled submarines, AUVs are able to follow a preset trajectory [3].

AUVs offer many advantages, e.g., they do not require a human operator, leading to a reduction in operational costs and increasing the safety for the workers. They operate in severe conditions and perform complex tasks [4]. The first AUV was developed at the Applied Physics Laboratory, University of Washington, USA [5]. The purpose was to study diffusion, acoustic transmission and submarine sinks. AUVs were also developed in the Soviet Union at the same time for similar proposes [6]. In the 1960s, AUVs were developed by the U.S. Navy to perform offshore rescue and salvage operations. Several industries have decided to use these devices for different tasks, e.g., the petrochemical industry to improve the development of offshore oil fields [7]. In the 1980s, AUVs came into a new era, being able to operate at high depths. Falling oil prices and a global recession resulted in a stagnant period in terms of AUV development in the mid-1980s. During the 1990s, there was a renewed interest in AUVs in research universities, and the first commercial prototypes appeared: e.g., OKPO 6000 by Daewoo (Fig. 1). This research was followed by more commercial AUVs in the 2000s [8]. Since then, these vehicles have experienced a great development. There are new designs, for

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Fig. 1. Korean AUV, OKPO-6000, that can dive up to 6,000 meters, developed by Daewoo Heavy Industries Ltd. (DHI) [104].

Fig. 2. "La Folaga" by GRAALTECH.

example, GRAALTECH AUVs (Fig. 2) that are now being used in a wide range of applications such as tracking down historic ship wrecks, e.g., the sunken ships inspection, mapping the offshore floor, object detection, ensuring harbor safety and searching for sea mines, etc. [9].

This paper considers a novel, complete and updated survey of the main instrumentation and measurement systems embedded in AUVs, including future uses and development. The paper is a synthesis of the main and current navigation, mapping and sampling technologies and different applications.

Literature Review

Nowadays, the technology used in AUVs is considered relatively complex due to the morphology of the vehicles and the working conditions underwater. It will contain certain systems and sensors regarding to the required work. There are general configurations in the market, e.g., Dorado class from Monterey Bay Aquarium Research Institute (MBARI) AUV (Fig. 3), and products developed by specialized offshore inspection companies as MBARI [10], JAMSTEC [11], Atlas Elektronik [12], KONGSBERG [13] or ALTUS [14], etc.

Functional Classification of AUVs

The embedded systems in AUV can be classified according to their functionality:

Propulsion or Drive System: Different systems and elements are used to impulse the vehicle, e.g., regarding to the steering rotor and propeller issues [15], with multiple shapes and materials in the market nowadays [16]. An appropriate propulsion system is set according to the vehicle morphology and use [17]. It is studied by aerodynamics and fluid mechanics scientists, taking into account the hull shape, where its design will be relevant for the correct effectivity of the vehicle [18]. There is some research about the optimization of the trajectory control and propulsion systems, using different mathematical and algorithmic advances related to the vectorial positioning of the vehicles, studying velocity and yaw components to improve

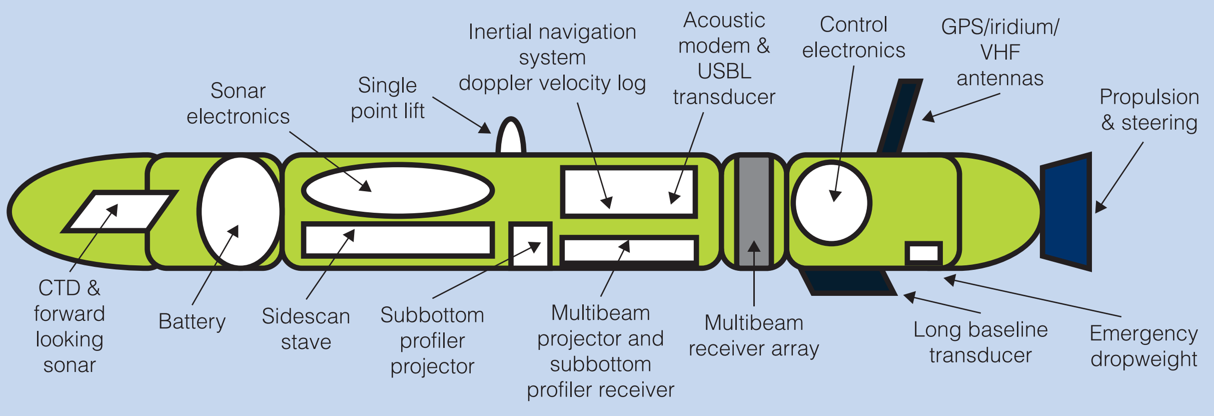

Fig. 3. Typical structure of an AUV. Design of the MBARI mapping AUV [105].

Table 1 – Summary of navigation and mapping embedded systems in AUV for Underwater Offshore Inspections

Application	System	Sensor Technology	Features	Ref.
Navigation	CTD/Sonde	Geophysical sensor	Different simple and single sensors that properly configured and assembled, can form a functional block like tracking and positioning applications.	[46], [47]
	Gyroscope	Geophysical sensor		[48], [49]
	Magnetometers	Geophysical sensor		[50], [51]
	Accelerometer	Inertial sensor		[29], [50]
	Barometer/Pressure Sensor	Inertial sensor		[52], [53]
	Doppler Velocity Log (DVL)	Inertial Sensor	Measure the velocity of the AUV with respect to the ground. The position estimation accuracy can improve greatly by Kalman filter. DVL will consist of 4 or more beams.	[43], [54]
	Baseline (Long/Ultra Short)	Beacon (Acoustic)	They can provide a complete ubication information of the AUV, however, these methods could present information delay and low measurement accuracy, producing stability errors.	[55], [56]
Mapping	Sidescan	Imaging Type Sonar (Acoustic)	Intensity of returns measure to originate 2D seabed image. Beams are directed perpendicular to route direction. Phase correlation and preprocessing methods have been used to improve the system.	[57]–[60]
	Multibeam echosounders	Rating Type Sonar (Acoustic)	Improving the single beam, obtaining a full coverage measurement in the area, wide range, high sensitivity and broadband response with high sensitivity. Work with time from returns form bathymetric maps.	[61], [62]
	Subbottom Profilers	Rating Type Sonar (Acoustic)	Low frequency echosounders that investigate the seafloor.	[62], [63]
	Forward Look	Imaging Type Sonar (Acoustic)	Similar method to a side-scan sonar, but with directed forward beams. Recent studies use this method combining with convolutional neural networks for objects detection.	[64]–[66]
	Camera	Geophysical sensor (Optical)	Optical graphics capturing and imaging processing. Relevant method for biological and geological surveys.	[67], [68]

AUV mission autonomy [19], [20]. AUVSIPRO is a simulation software developed for performance prediction with different propulsion system configurations [21], providing an effective method for the hull hydrodynamic study.

Power Sources: The most common warehouse and storage methods are the standard commercial batteries developed, e.g., magnesium-seawater battery [22], a pressure tolerant Li-ion battery [23] and an aluminium-hydrogen peroxide (Al/H_2O_2) semi fuel cell [24], where different types of them, e.g., alkaline cell or fuel cell, are used depending on the function of buoyancy changes, system simplicity or depth requirements [25]. There are novel energy sources under research now, e.g., based on hydrogen fuel cells or the combination of the aforementioned systems, using the renewable energies of special interest [26], [27].

Navigation and Positioning Systems: These vehicles work in large offshore areas and need proper systems and methods to guide their trajectories. It is important to have reliable navigation and positioning for underwater surveys. AUV navigation and localization techniques can be divided according to three categories: Acoustic transponders and modems [28]; Inertial/dead reckoning [29], [30], and; Geophysical techniques [31]. They consist of hardware and software architecture systems, e.g., the well-known Extended Kalman Filter [32], [33], range-only localization [34] and light beacons algorithmic combinations [35], [36].

Mapping and Sampling Systems: They monitor different areas or the seabed by generating 2-D and 3-D operational maps employed in multiple applications, e.g., sonar technologies [37]. The main and current sensors used for this issue are detailed in Table 1. The optical cameras often employ LED illumination due to the darkness present in submarine work, allowing a wide range light condition [38]. The information collected by these systems can be transferred to audiovisual documents, providing real time remote exploration in some cases, employing techniques as submarine image processing approaches, e.g., image de-scattering process, image high definition assessments and image color restoration [39]. The number of studies about the optical capture and camera systems is rising due to the importance of graphical documents for maintenance works [40].

Features of Applied AUV Systems

One of the main advantages of AUVs is their ability to work following a programmed route. There are several methods to follow these routes, for example, using acoustic beacons on the seabed, GPS location, baseline acoustic communication, inertial navigation. It could be based on the combination of Conductivity [41], Depth and Temperature (CDT) sensors [42], inertial sensors and Doppler Velocity Logs (DVL) [43]. In contrast to gliders, that use a buoyancy engine and follow a wavy path, AUVs are able to retain a linear route through the sea [44]. For this reason, these vehicles are suitable for geoscience applications that require a constant altitude, such as seabed mapping and sub-bottom profiling remotely, allowing tasks in a remote area [45].

Table 1 summarizes the main uses, properties, methods and references of the sensory systems, doing a dissertation between navigation and cartography mapping applications, although the uses of groups are not exclusive. The systems and sensors could appear in multiple commercialization configurations.

The sensors and peripheral systems are often combined in one programmed functional system to provide improved performance, e.g., navigation, mapping or drive systems. Until now, the systems implemented in AUVs such as multibeam echosounders (MBES) [69], side-scan sonar (SBP) and sub-bottom profilers (SSS), together with the photography of the seabed, have managed to satisfy the requirements for underwater offshore cartography [70]. However, the development of sensors is now focused on monitoring the water column. The Natural Environment Research Council (NERC), in 2000, developed the first geochemical sensor implemented for an AUV called Autosub, that was fitted with a manganese analyzer in 2003 [71] and 2005 [72]. These systems demonstrated that the chemical sensors embedded in the AUV can detect variation in small ranges of distribution of chemical elements, not resolved by traditional sampling methods. Since then, the chemical sensors developed in the AUV for geosciences in the high seas have been used mainly in the search for active hydrothermal plumes in the water column [73] or for detecting active methane venting [74]. Nevertheless, the kind of navigation a mapping system uses depends on the different operations or mission objectives. The main considerations are the required location accuracy and the size of the region of interest. Combining these variables can allow a higher performance in the underwater vehicle [75], e.g., the simultaneous localization and mapping (SLAM) technology [76].

The general approaches to solve AUV positioning and localization are based in ultrashort baseline (USBL) [77] and long baseline (LBL) [78], and require a localized and preassigned infrastructure. Nowadays, SLAM is focused to a dynamic multiagent system, allowing quick flexibility and deployment with the lowest facilities [79]. Furthermore, these techniques developed for surface robotics applications [80] are being redeveloped for underwater uses, optimizing the navigation design and operability of these vehicles and missions [44].

The functional outline showed in Table 1 should be correctly coupled in a complex control system. Fig. 4 shows an example of the AUV control unit design process, considering the aforementioned systems and developing interconnection between different systems by a microcontroller [81]. The vehicle's primary design phase considers the interchangeable elements, with easily extractable parts for maintenance work and optimal space distribution.

An important challenge for AUV development are the telecommunication technologies, due to the complexity of the marine and submarine environment [82]. One of the key

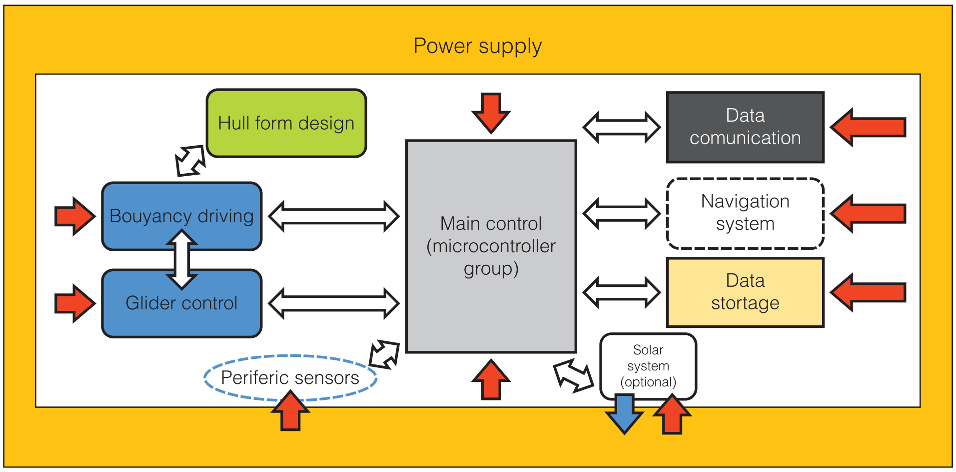

Fig. 4. AUV Control unit block diagram.

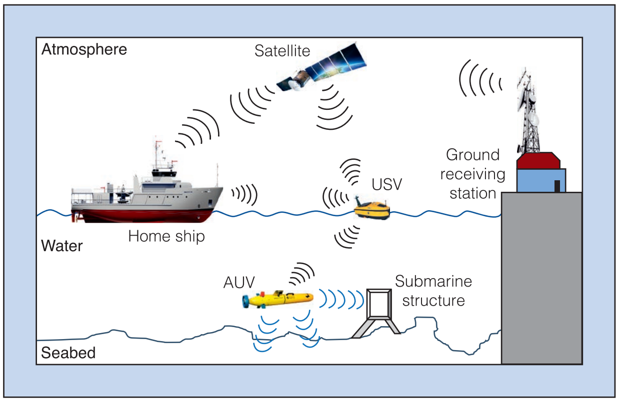

Fig. 5. AUV and ASV (Unmanned Surface Vehicle) Telecommunication system.

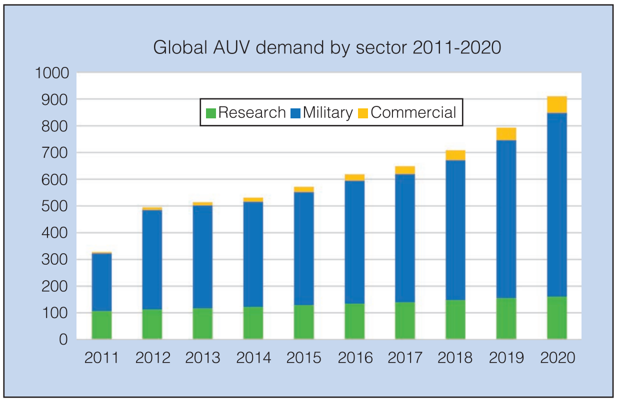

Fig. 6. Global AUV demand by sector 2011-2020 [97].

factors about compression and communication architecture [83] is the bandwidth and distances between AUV and the Remote Monitoring and Control Centre (RMCC), or home ship limitations [84]. These factors will determine the correct choice of hardware and software configurations for each purpose [85]. Underwater environment limits the use of regular electromagnetic signals, such as radiofrequency (RF) [86] or Wi-Fi [87]. Together with the non-homogeneous density of seawater due to salinity or temperature, it leads the use of acoustic modem technology bandwidth-limited in the range of kbps, with long connection gaps [88]. There are some proposals combining data transmission in submarine technology by using geo-positioning systems, such as Global Positioning System (GPS) [89] or Global Navigation Satellite System [90] and Wi-Fi, 4G or L-band for aerial data connections, and using these for RMCC, satellite and vehicles communications [91], [92] (Fig. 5).

Discussion and Future Challenges

The instrumentation and measurement systems for AUVs are not thoroughly studied in the literature. The main paradigms to cover in AUVs include progress in routing, mapping sonar, energy storage and drive systems. Non-linear mathematical methods for the control units are beginning to be used [93] to cover the needs of new and advanced materials, e.g., "smart materials" [94] and vehicle shape and morphology, for modifying hydrodynamic conditions using flexible hull with new composite materials above mentioned, and modulating the drag and mass qualities of the hull to get better control of the vehicle's forward speed.

The current irruption of transcendental markets in both commercial and defense government departments has led to increased activity of transforming the research to industrial production of AUVs. Demand in 2020 is forecast to be 105% higher than 2016, but the commercial demand will be only 4% of total AUV demand [95] (Fig. 6). The curve of applications time evolution of these vehicles shows a state of economic benefit, illustrated in Fig. 7. It is encouraging an outstanding development drive on the part of component suppliers to customize their product manufacture to improve the AUVs [96]. The outcome is a quick growth of AUV performances [97].

Some recent studies about offshore mapping, the meticulous testing of sea resources and ocean infrastructure inspections have clearly demonstrated the validity and effectiveness of ROVs and AUVs configured with suitable acoustic and imaging systems [98]. These vehicles stand out in the acquisition of data that allow the definition of the seafloor morphology and topology, the evaluation of underwater habitats and the analysis of marine infrastructure [99].

Management politics and legal implications about AUVs are important requirements for increasing the reliability of AUVs in the scientific sector due to the high cost of equipment employed and the data collected. This interest has generated several studies to evaluate and manage the risk associated with AUV improvements [100]. The increasing use of AUVs will demand updating in relation to legal matters and diplomatic authorization. Probably these rules will be different for each type of user, i.e., commercial, military or scientific research [101]. The legal definition of AUV generates many doubts regarding the kind of vehicle classification. These bureaucratic issues will become important in situations of rescue, dangerous trajectories, incursions in unauthorized areas,

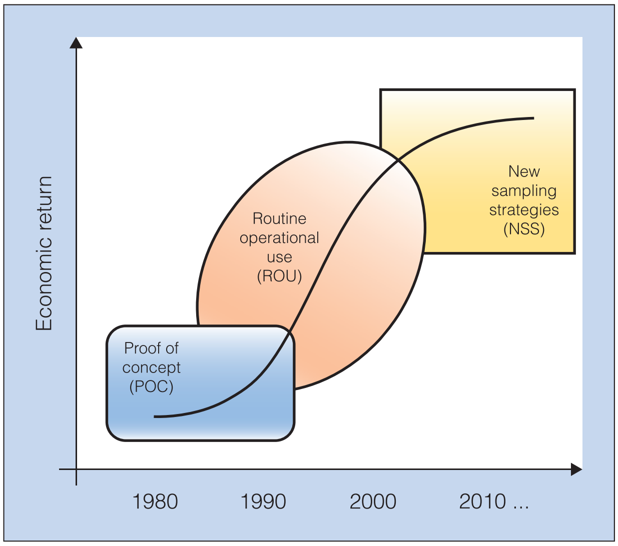

Fig. 7. Possible timetable for the development of AUV technology shows a current state of continous research strategy for the future economic return [8].

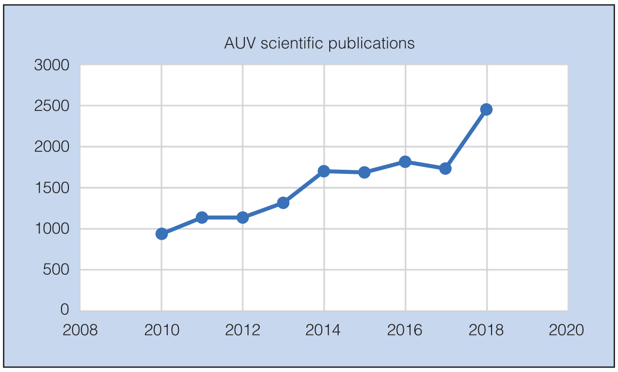

Fig. 8. AUV scientist publications over time [106].

equipment failures or collisions [102]. Other benefits of underwater vehicles observed related to dangerous and extreme weather condition areas are the new vehicles, tools and configurations for frozen environments explorations in polar regions, allowing biological and geo-chemical research [103].

According to the literature review, this paper concludes that AUV research progress could be decisive for enterprise, scientific, economic and government advancement. It is being reflected in the number of the research publications over time (Fig. 8) with important growth in the last years.

Conclusions

Autonomous underwater vehicle development is an essential field for scientific research for industrial and military applications. Ocean explorations need the development and application of new technologies. The topics to cover are, for example, physiognomy design, sensors systems, communications, navigation systems, power endurance and propulsion systems.

The main contributions of this paper have been a general, complete and updated review of the state of art in the principal instrumentation and measurement systems embedded in AUVs. It also detailed their future uses and development, summarizing the main and current navigation, mapping and sampling technologies and their applications.

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