Key Features of the Autonomous Underwater Vehicles for Marine Surveillance Missions

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Abstract. This paper gives an overview of autonomous underwater vehicles' (AUVs') applications, shapes due to the specific kinetic and dynamic requirements, state estimation, control, navigation and communication principles. The emphasize is put on AUVs deployed within EU Horizon 2020 COMPASS2020 (Coordination Of Maritime assets for Persistent And Systematic Surveillance 2020) project for marine surveillance and reconnaissance missions in European seas. Basic data facts on the AUVs delivered by ECA Group are given, along with some general directions for further research in the filed with the aim of achieving more efficient and environmental friendly underwater missions in the future.

Keywords: Autonomous Underwater Vehicles (AUVs), key features.

1 Introduction

Two main types of unmanned underwater vehicles are: (i) remotely operated underwater vehicles (ROV) and (ii) autonomous underwater vehicles (AUV). The ROVs are controlled from the surface by a wired connection. These can do many different tasks, but the wired connection restricts their maneuverability and capacities to reach remote areas. The AUVs navigate autonomously due to the dedicated navigation algorithms and collect surrounding information. Once launched, they collect data and come back to the surface after completion of their specific task. Since AUVs are not connected via wire to the ship or ground they have high maneuverability, powered by battery or fuel cell, they can reach remote locations, follow narrow composite pathways, avoiding at the same time human fatigue and reducing operation expenditures.
In this paper, emphasize will be put on AUVs. These are very versatile autonomous systems and can be used for numerous purposes as: (i) military (surveillance, anti-submarine warfare, mine countermeasures, site inspection, inspection of wreckage, payload delivery to ocean floor, search and rescue, aircraft crash investigation, i.e. black-box search and retrieval during the investigation, ocean exploration and bathymetric study, mapping of ocean floor, locating and retrieval of dumped illegal loads, etc.); (ii) scientific (marine biology studies, close-up observations of aquatic life without disturbance, geological survey, archeological survey, underwater environmental monitoring in rivers and lakes, track oil-spill and gas leakage, etc.); (iii) industry (repair and maintenance, track and repair underwater cables and pipelines, underwater structure inspection, etc.); and (iv) other (underwater video footage collection, fishing, entertainment, sports, tourism, etc.) [1].

Within the COMPASS2020 project UAVs are used for environmental recognition, sensing, mapping and localization [2]. More precisely, in the combat with narcotic smugglers, illicit narcotic bundles (of cannabis, for instance) might be dumped from the smugglers’ speed vessels and police and/or military forces have to locate them and retrieve afterwards. Namely, once located, the positions of the crates and/or bags with narcotics are communicated to the authorities for their efficient retrieval. It is to be mentioned that COMPASS2020 can be treated as a kind of follow up of the SWARM (Smart and Networking UnderWAter Robots in Cooperation Meshes) project, which main objective was to develop an integrated platform for autonomous maritime and underwater operations including AUV, aerial autonomous vehicles (AAVs), ROVs and unmanned surface vehicles (USV) performing dangerous missions [3;4] in multimodal modes. Similar is with COMPASS2020 project, which has to integrate several AAVs as Zephyr, AR5 Life Ray Evolution, AR3 Net Ray, operating at different altitudes and providing in such manner broader coverage at different resolution levels [5]; sea surface speed patrol vessel; and, AUVs.

The rest of the paper is organized as follows: Section 2 contains key features of AUVs including their technical detail, shape, navigation and communication principles; Section 3 provides short description of AUVs deployed within COMPASS2020 project; while Section 4 gives some conclusion remarks and directions for further research work in this domain.

2 Key features of AUVs

The idea of designing and developing AUVs is not a new one. The first AUV, or the self propelled underwater research vehicle was developed by Murphy and Francois in 1957 in the Applied Physics Laboratory at the University of Washington (USA). This craft operated at 2-2.5 m/s up to a depth of 3600 m. In the 1970s few
AUVs were developed in MIT and also in the Soviet Union [1]. These early underwater robots were heavy, expensive and inefficient. Today’s AUVs can have six degrees of freedom, travel faster than 20 m/s, accurately detect obstacles and map ocean floor at depths of up to 6000 m. They are more sophisticated, less expensive and consequently accessible for wider exploitation like fishing, sports, tourism, entertainment, etc. However, AUVs have yet to go a long way in terms of becoming fully autonomous, capable to explore deep and hazardous underwater habitats. In Table 1 are given some basic data on actual AUVs producers, AUVs’ applications and key technical features.

**Table 1.** Actual AUVs types, producers, applications and basic features [1;5;6].

| Heading level | Applications                                      | Dimensions                  | Depth   |
|---------------|---------------------------------------------------|-----------------------------|---------|
| AE1000, Japan | Inspection of underwater telecommunication cables | 2.3 m x 2.8 m x 0.7 m       | 1000 m  |
| Maya AUV, NIO, Goa, India | Oceanography study                                      | 1.742 m, dia. 0.234 m       | 200 m   |
| Theseus AUV, Canada | Under-ice bathymetric surveys                  | 10.7 m, dia. 0.127 m        | 2000 m  |
| Autosub 6000, AUVAC, USA | Scientific survey and mapping                   | 5.50 m x 0.90 m x 0.90 m    | 6000 m  |
| HUGIN, Kongsberg | Seabed mapping, pipeline inspection, mine reconnaissance | 5.2-6.4 m, dia. 0.75 m      | 3000-4500 m |
| REMUS-6000, Kongsberg Maritime | Oceanography study, monitoring, surveillance, reconnaissance, etc. | 3.96 m, dia. 0.71 m | 6000 m |
| AUV-150, CMERI, India | Oceanography study, mapping, surveillance, reconnaissance, etc. | 4.85 m, dia. 0.5 m | 150 m |
| D. Allan B, MBARI, USA | Seafloor mapping                                       | 5.18 m, dia. 0.54 m         | 6000 m  |
| SOTAB, Osaka University, Japan | Track of leakage from oil mines                  | 3.0 m, dia. 0.27 m          | 200 m   |
| AE 2000A, Japan | Under-ice survey                                      | 3.0 m x 0.7 m x 0.7 m       | 2000 m  |
| Tri-TON 2, University of Tokyo, Japan | Estimate ore resources in underwater hydrothermal deposits | 1.4 m x 0.7 m x 1.4 m | 2000 m |
| SeaCat, Germany | Autonomous inspection of underwater structures     | 2.5 m x 0.58 m x 0.67 m     | 600 m   |
Inspired mainly from submarines, AUVs are generally torpedo shape. These are highly maneuverable and can exactly travel in complex pathways and access remote areas, without engendering human life. Some AUVs are of hydrofoil shape, while some other mimicked aquatic animals as snakes, turtles, beetles and crabs. So called, fish robots are mostly popular among the bio-mimetic AUVs. As an example SoFi (Soft Robotic Fish) can be given (Fig. 1a/b). It is designed and developed by the team from MIT’s Computer Science and Artificial Intelligence Laboratory. SoFi is made of silicone rubber and enables closer study of aquatic life. In fact, it gets closer to marine life than humans can get on their own [7,8].

![SoFi in searching elusive marine environment](image1)

![SoFi’s key modules](image2)

**Fig. 1.** SoFi UAV (Source: Web)

The AUVs are often equipped with different acoustic sensors like side scan sensors, forward looking sensor, or multi-beam echo sounder, etc. They are usually of modular structure, containing propulsion, sensing, controlling, navigation, communication and other modules. These modules can be easily and quickly replaced in the case of malfunction and/or for the purpose of different missions. The AUVs usually produce low level of noise (or no noise at all in some cases) and consequently don’t disturb aquatic ecosystem.
2.1 Navigation principles

The AUVs navigate underwater autonomously based on predefined plan. Localization is of key importance in navigation, since it enables AUV to follow the predefined path precisely and reach the final destination. As Global Positioning System (GPS) does not function underwater and high frequency radio signals propagation in the underwater environment is suppressed, localization and navigation are very challenging for AUVs. When using GPS, AUV has to resurface in intervals. In general, methods of AUVs navigation can be broadly divided into inertial, acoustic and geophysical.

**Inertial navigation.** An embedded inertial navigation system (INS) is a navigation device, based on submarine of worldwar, that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously estimate by dead reckoning the position, the orientation, and the velocity (direction and speed of movement) of a moving object (here AUV) without the need for external references [9]. INS is usually used for small, inexpensive UAV, since over the time it can accumulate errors generated by accelerometer and gyroscope [1]. An regular recognition is needed to compensate the drifting.

**Acoustic navigation.** When it comes to acoustic navigation, the range is estimated from the time of travel of the acoustic signal from AUV to the external transducers (devices, which generate and receive sound waves) and backward. The AUV position is known in real time thanks to calculating on the principle of triangulation. Three different types of acoustic navigation are briefly described below:

(a) In the case of Ultra-Short Baseline (USBL) the AUV is positioned relative to a surface vehicle fitted with an array of acoustic transducers (Fig. 2.b). Relative distance is calculated from the time of travel of the acoustic signal and direction from the phase difference of the signal received by different transducers. Here the transducers are placed close to one-another and major disadvantage is precise range detection.

(b) In the case of Short Baseline (SBL) the transducers are placed in front and back of the surface vessel (Fig. 2.b). Therefore the baseline is limited to the length of the vessel, which limits the positional accuracy of the AUV.

(c) In the case of Long Baseline (LBL) the transducers are widely placed over the mission area on the seabed (Fig. 2.c). Localization is done by triangulating the range estimated by acoustic transducers. The major limitation is the huge cost and time involved in placing the transducers on the seabed [1].
Geophysical navigation. When it comes to geophysical navigation, external environmental features are used as landmarks for positioning. Optical and sonar are two main modes of geophysical navigation. Simultaneous localization and mapping is predominantly used for it [1]. In the case of optical navigation, monocular or stereo cameras can be used to take images of the underwater environment and features extracted from the images can be used for simultaneous localization and mapping (SLAM). In such setting different visual odometry techniques are used. On another side, high-power SOnund NAvigation and Ranging (SONAR) is a device for detecting and locating objects especially underwater by means of sound waves sent out to be reflected by the objects. Sonar is a commonly used technique for communication, detection of objects, and navigation by using sound propagation. A comprehensible description of Sonar can be found in [10] and it states: “When AUV is used to map the topography of the ocean’s floor, it sends out sound pulses, often referred to as pings, towards the bottom of the ocean within its vicinity. As these sound pulses travel downwards they will encounter physical features such as hills, valleys, rock, etc. These sound pulses are subsequently reflected back up towards the AUV, having been modified by the objects along their path. These reflected pulses are often called echoes. Receivers on the AUV that detect these echoes can then reconstruct the topology of the region from which the echoes bounced off. Sonar is very like the echosounder. The difference is that the sound beam can be steered in the desired directions and present images of the bottom topography on suitable display. Synthetic Aperture Sonar (SAS) is a relatively new principle in hydroacoustics. Together with advanced image processing the method can produce very detailed images of sea bed and objects. It operates in such way

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1 Odometry is the use of data from motion sensors to estimate change in position of an object (here AUV) over time. It is used in robotics by some robots (for AUV, too) to estimate their position relative to a starting location. The word odometry is composed from the Greek words odos (meaning “route”) and metron (meaning “measure”).

2 Marriam Webster Dictionary. Retrieved from: https://www.merriam-webster.com/dictionary/sonar (last access: 10th April 2020).

3 Originally submarine.
that one moves sonar along a line and therefore illustrates stationary objects from several directions. The transmitting antenna’s synthetic aperture in relation to the object will then be the length the sonar has moved (Fig. 3). These systems that are now in use can give resolution of 2x1 cm, which is typically 10 times better than what ordinary sonars can give. Kongsber produces an SAS (HISAS-1030), which is used at AUV Hugin (Fig. 4). It works at 70-100 kHz and can be delivered with Focus software [11].

Some AUVs should have ability to carry out long-distance missions fully autonomously and without supervision from surface ship. Combined with inertial navigation, the use of one or several transponders on the seabed is an accurate and cost-effective approach towards achieving this [12;13]. An extensive description of actual advanced AUVs’ propulsion solutions, control systems and their key components, state estimation methods, path planning models and techniques along with object detection and obstacle avoidance can be found in [1;14].

2.2 Communication principles

Underwater wireless communications are implemented using communication systems based on acoustic, radio frequency, and optical (light and laser) waves. Underwater acoustic wireless communications have been one of the most used technologies since they can provide connection over rather long distances (Fig. 5). However, acoustic waves have many drawbacks as scattering, high delay due to
the low propagation speeds, high attenuation and low bandwidth. Additionally, acoustic signals generated by communication systems and sonar devices have harmful impact on the underwater mammals and fishes. Therefore, research has been carried out in the past to use low frequency radio waves (30-300 Hz). These waves have numerous disadvantages like high attenuation, low data rate, adverse effect of shallow areas, long antennas, etc. For worldwide communications with submarines, e.g., for depths up to a few 10 m very low frequency (VLF) transmitters from 10-30 kHz are used. In oppose to acoustic and radio waves, optical waves can provide high-speed underwater optical communications at low latencies, thanks to high propagation speed and high data rate in return for a limited communication range (tens of meters). In Table 2 are given key features of underwater acoustic, radio and optical wireless communications.

Table 2. Underwater acoustic, radio and optical communications features [15, p.3].

| Feature          | Acoustic | Radio     | Optical   |
|------------------|----------|-----------|-----------|
| Range            | < 20 km  | < 100 m   | 100-200 m |
| Attenuation factors | Conductivity | Conductivity and frequency | Distance vs. inherent optical properties |
| Speed            | 1500 m/s | 2.25x108 m/s | 2.25x108 m/s |
| Power            | 10 W     | 100 W     | 1 W       |
| Cost             | High     | High      | Low       |
| Data rate        | < 10 Kbps | < 0.1 Gbps | < 10 Gbps |
| Antenna size     | 0.1 m    | 0.5 m     | 0.1 m     |
| Latency          | High     | Moderate  | Low       |
Fig. 5. Average achievable transmission distance by various commercial acoustic modems 
(Source: [15, p.2])

All three considered underwater wireless communication modes have certain advantages and disadvantages dependant of various underwater conditions. The subject remains open and further research is necessary for conceiving and implementing more practicable and accurate communication, networking and localization schemes [15].

3 The AUVs deployed in COMPASS2020 project

One of the COMPASS2020 project main goals is to develop an integral platform for efficient simultaneous deployment of unmanned aerial vehicles (Zephyr, AR5 Life Ray Evolution, AR3 Net Ray), offshore patrol vessel (OPV), and underwater autonomous vehicles (A27 and A9) for preventing and combating trafficking of narcotics over European borders. To illustrate the impact of narcotics in Europe, it is estimated that every year approximately 125 tonnes of cocaine are consumed. The majority of it comes from Latin America to Europe on transatlantic routes. However, in recent years transhipments from large vessels to various forms of transport (including leisure sailing vessels, fishing vessels, merchant vessels and fast speedboats) have started occurring in sea waters along Northern and Eastern African coast. These new forms of transport target mainly Spain and Portugal as points of entry, while the most traditional forms target Belgium and the Netherlands (major European shipping ports) [16]. When it comes to interception of narcotics smugglers – the OPV, the Zephyr and the AUV are in action in the border area. The Naval Group Mission System (MS) is running onboard the OPV and it is always connected with its replica at Marine Operations Center (MOC) ashore. Zephyr is launched from MOC and it has to collect an overall picture of the area
that is being surveyed. In addition, the AUVs should be previously deployed from the OPV into a strategic location that is coincident to the traffickers' typical routes. The AUVs are programmed to follow specific trajectories in the area of interest, navigating underwater at low depth in order to remain undetected from the smugglers and at the same time staying closely enough to the surface in order to optimize the possibility of detecting the target. The low noise AUVs carry of a streamer of hydrophones\(^4\) wide bandwidth that enable detecting speed boats. After detection of the target, the AUVs can communicate to the Zephyr, thanks to the OPV which is used as a communication relay in the system. The Zephyr sends automatically an alert to MS onboard OPV and its replica in the MOC. Once the MOC receives the alert, the officers proceed with the deployment of an AR-5 platform\(^5\). The AR-5 has to come close to the vessel and acquire more detailed information about it. In accordance to this information, the officer onboard OPV can decide how to intercept the threat and act efficiently. If the smugglers try to get rid of the cargo, UAV and AUVs have the capacity of searching for it by making use of sonars\(^5\)\(^2\). In the following two subsections, short descriptions and some basic data on the AUVs employed within COMPASS2020 will be given.

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\(^4\) A hydrophone is a microphone designed to be used underwater for listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates an electric potential when subjected to a pressure change, such as a sound wave (in this case caused by narcotic smugglers' vessel / the author's comment) [Source: Wikipedia].

\(^5\) Side-scan sonar is a category of sonar system that is used to efficiently create an image of large areas of the sea floor. Side-scan sonar imagery is also a commonly used tool to detect debris items and other obstructions on the seafloor that may be hazardous to shipping or to seafloor installations by the oil and gas industry. In addition, the status of pipelines and cables on the seafloor can be investigated using side-scan sonar (in this case its used for detecting abandoned bundles with narcotics / the author's comment) [Source: Wikipedia].
3.1 The A27 AUV

The A27 is a development of ASEMAR of ECA Group Autonomous Underwater Vehicle family (Fig. 6). Big Size AUV with long endurance and high payload capability can be used for both the defense and to commercial purposes. It performs autonomous missions up to 300 m depth, and is easily transportable by plane for overseas missions. Due to its large endurance, very high area coverage rate (2km²/hour) and payload capacity, it is able to host high performance payloads according to the mission’s requirements: Synthetic Aperture Sonar (SAS), video, forward looking sonar (FLS), multi-beam echo sounder, and others [17]. For navigation it uses Inertial Navigation System (INS), Doppler Velocity Log (DVL), military global navigation satellite system (GNSS) and Global Positioning System (GPS) periodically, after resurfacing. It can communicate via WiFi, Ethernet, Iridium and/or acoustic wireless communication channel. Its average speed is 3-5 knots (and max 6 knots). Key payloads are Sonar and Conductivity, Temperature and Depth (CTD) sonde. It withstands harsh environmental conditions and offers a greater stability when encountering heavy turbulence from waves. The high degree of stability enables this AUV to capture high-resolution images. The information obtained by the platform is post-processed in the command centre [18].

![Fig. 6. The A27 AUV](Source: COMPASS2020 documentation)
3.2 The A9-E AUV

The A9-E AUV is the configuration of ECA Group for environmental monitoring (Fig. 7). In addition to the seabed image acquisition, it can record bathymetric data as well as environmental information such as water turbidity, conductivity, temperature, fluorescence, dissolved oxygen and/or pH. Mission planning and monitoring are done through user friendly software which allows operator to follow the vehicle at any time during its mission. This underwater drone has been designed to meet STANAG 1364 requirement, i.e. its acoustic and magnetic signatures are minimized in order not to trigger any underwater mines when doing the mine warfare survey. As part of early trials for the SWARM project, ECA Group’s A9 AUV fitted with the interferometer side-looking sonar demonstrated ability to conduct surveys in a shallow water environment of 50m depth. It uses a phase differencing bathymetric sonar that increases area coverage by close to 200% over conventional multi-beam echo sounders in shallow water [19]. For navigation it uses INS, DVL, GPS and for communication purposes radio (UHF), WiFi, Ethernet and the acoustic wireless communications. Its payload consists of, but it is not limited to: Interferometer Side Scan (ISS) sonar, video, CTD, environmental sensors (turbidity, pH, fluorescent Dissolved Organic Matter (fDOM) / waste water discharge), etc [20].

![Fig. 7. The A9-E AUV](Source: ECA Group Web site)

4 Conclusion

The paper gives an overview of some key determinants of AUV. These systems have a variety of military, scientific, industrial and other applications. They can be very complex and expensive, but there are some that are available for educational and recreational purposes. It is a common opinion in the literature that these systems have been developed to a very high standard, but that there is plenty of room for further research and improvement when it comes to: better adaptive control
techniques using neuro-fuzzy techniques, more accurate localizing using improved INS non-linear Kalman filters, cooperative localization (swarm intelligence), artificial intelligence vision and object detection, odometry, underwater wireless communications, high-density battery power supply, energy harvesting methods, etc. By improving all these dimensions, AUVs will become fully autonomous long-range underwater robots, capable to explore the deepest, inapproachable and harsh corners of the seabed. In the case of considered COMPASS 2020 underwater autonomous vehicles have to be integrated into the complex system composed of autonomous aerial vehicles (Zephyr, AR5 and AR3), sea surface vehicle (OPV), including Naval Group mission system (MS) onboard OPV and shore based marine operations center (MOC). At the moment, the experts’ team within the project is designing algorithms for seamless data acquisition, analysis, storage and presentation. This research work is based on the experts’ knowledge, skills and experiences acquired through several realistic case studies and recent test-beds in European seas. Following research work should target harmonizing actions of all involved man and unmanned vehicles and optimizing relevant data/information flow schemes. In parallel, improving bidirectional communication links between all involved parties in the case of emergency are to be further explored.

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