THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE XI – SHIPBUILDING. ISSN 1221-4620, e-ISSN 2668-3156
2020

UNDERWATER ROBOTICS – TECHNICAL ASPECTS ON AUTONOMOUS UNDERWATER INSPECTION VEHICLE

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ABSTRACT

This article is devoted to a state of the art on mobile multi-robot systems in the underwater domain. It starts with the history of underwater robots as well as their applications in various fields, then focus on underwater vehicles different categories characteristics and properties, their appearance and their applications. Subsequently, the design of an autonomous underwater inspection vehicle is presented together with its functions, movements and control system.

Keywords: underwater robots, remotely operated vehicles, autonomous underwater vehicles

1. INTRODUCTION

Covering about two-thirds of the earth, the ocean has a great effect on the future existence of all human beings. About thirty-seven percent of the world's population lives within 100 km of the ocean. Despite this, researchers and robotics scientists have focused more on exploring the Earth's environment and studying atmospheric phenomena. The exploration of the depths and the exploitation of its resources constitute a major economic issue and a challenge that current technologies do not yet allow to respond. For example, it is estimated that there are about 2,000 billion tonnes of manganese nodules on the floor of the Pacific Ocean near the Hawaiian Islands. The researchers also discovered, using manned submersibles, that a large amount of carbon dioxide comes from the seabed and from extraordinary groups of organisms living in hydrothermal areas.

Underwater robots including unmanned vehicles and autonomous underwater drones can help us better understand marine environmental issues, protect ocean resources from pollution and use them effectively for human well-being.

2. HISTORICAL

The history of underwater vehicles is not recent. We can cite in chronological order the development of research in this field.

The first attempts at the practical implementation of this idea are reported as early as the time of Alexander the Great, who, according to Aristotle, had developed a primitive submersible for recognition missions in 322 BC. A similar machine had been developed in China around 200 BC.

During the modern era, the Englishman William Bourne took a first step towards the concept of an underwater vehicle in 1578, designing a sealed model that could be supplied with oxygen. But his ideas did not get beyond the design stage.

Between 1620 and 1624, the Dutchman Cornelis Van Drebbel would have sailed a few meters under the waters of the Thames. In 1664, he would offer a first underwater vehicle advancing using 12 rowers equipped with special oars. Having an ovoid shape, it could be actuated so as to achieve vertical movements. It has even been tested experimentally.

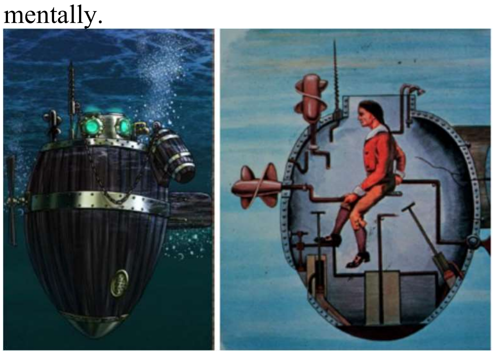


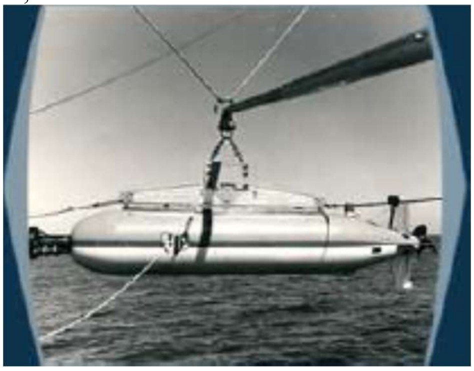
Fig.1. Bushnell's submarine

In 1776, the first American submarine vehicle "Turtle" was presented by David Bushnell and his brother (see Figure 1). Built of steel, it could move around independently. It is the first to be, on the one hand equipped with propellers for its propulsion and on the other hand with a valve for immersion and ascent to the surface. It was the first autonomous submersible engaged in naval combat.

Since that time, underwater vehicles have greatly evolved in terms of their source of power. The research aimed to dispense with human propulsion and harness other sources of energy. The French Navy Plongeur, launched in 1863, was the first submarine equipped with a compressed air motor and 23 tanks of 12 bar pressure.

In 1888, Le Gymnote was the first submersible of the French navy, equipped with a 55HP electric motor powered by 564 accumulators. Smooth and tapered in appearance, the Gymnote was 18m long. Its diameter, in its widest part, was barely 2m. Although built for military use, the Gymnote was later assigned to experimental missions.

The Spanish Isaac Peral built the first fully operational submarine in electric power. Tested at sea on September 8, 1888, it possessed two torpedoes, new air systems, a propeller and control surfaces, thus beating future submarines. Despite the short life of its batteries, it could reach 10 knots underwater.



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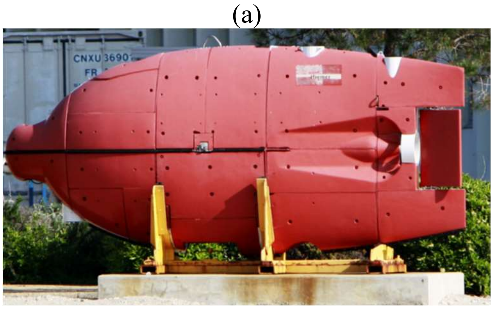


(b)

Fig.2. The first autonomous submarines (a) The SPURV (USA, 1977), (b) The killer whale (France, 1967).

With the turn of the century, the development and use of submarines has changed dramatically. With the emergence of many technologies and innovations such as the generalization of the periscope on the majority of submarines of the time and the predominance of diesel-electric propulsion in terms of energy, the rate of adoption of desk pads by many navies s is strongly accelerated. In the 1950s, nuclear power began to replace diesel-electric propulsion. The first autonomous underwater vehicles were developed during the years 60-70 with:

- The SPURV (Self-Propelled Underwater Research Vehicle, USA, 1977): weighing 480 kg, it could reach a speed of 2.2 m/s for 5 hours in a row with a maximum immersion capacity of 3000 m. It was used to make conductivity and temperature measurements applied to wave modeling (see figure 2a).

- The killer whale (France, 1976): weighing 3 tonnes, it could reach a speed of 12 knots for 7 hours in a row with a maximum immersion capacity of 6000 m and maintain an acoustic connection with the surface (see figure 2b).

3. UNDERWATER VEHICLES

Since the end of the 20th century, underwater vehicles have greatly evolved from a technological point of view. We can classify them into two categories: submarines and submarine robots, of which we are going to make a quick inventory. They also represent the ancestors of underwater vehicles in regular activity around the world.

3.1. SUBMARINES

The first category of underwater vehicles are submersibles and submarines:

- Submarines are large vehicles maneuvered by a crew, who may reside there during the mission period, especially in a military context.

- Submersibles are small and are intended for exploration of great depths. Their main missions were: the search for hydrothermal vents in the oceans; interventions on wrecks; etc.

3.2. UNDERWATER ROBOTS

An underwater robot is an unmanned underwater vehicle. It is both automatically propelled and equipped with a power source on board or supplied by its carrier boat. It can be controlled remotely (usually wire-guided) or stand-alone. These robots are fast in data acquisition and have a great capacity to secure any type of information (physical, acoustic, visual) in digital form according to their storage and processing capacities. Some were used as a platform equipped with samplers or various sensors. This makes their use a potential source of scientific and industrial progress. The robotics community often uses the acronym "UUV" ("Unmanned Underwater Vehicle") for these vehicles. The degree of autonomy (decision / energy) of these robots is defined by the nature of its connection with the surface (see Figure 3). We can then decide on a first classification broken down into two categories of underwater vehicles: remotely operated vehicles linked by a cable to the surface and autonomous vehicles linked by an acoustic link.

Below is presented an inventory of the different types of robots existing in each category.

3.3. REMOTELY OPERATED UNDERWATER VEHICLES (ROVs)

These are devices controlled by an operator through a ground station or on a boat. They are connected to the surface via a cable through which the motor controls, energy and acquired data pass. The presence of the cable induces disturbances on the robot's dynamics and complicates its control, which disturbs its stability and affects its ability to perform the required tasks perfectly (see figure 3).

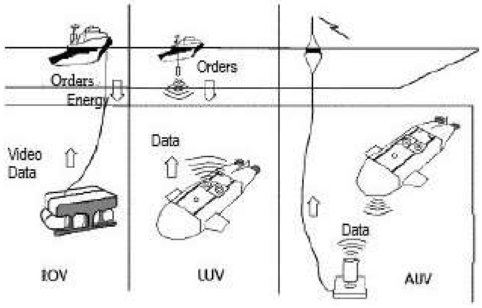


Fig.3. The different types of underwater vehicles.

However, its presence allows easier recovery of the vehicle. Some examples of ROVs can be cited such as the "observe" (from Subsea Tech) as well as the "L2ROV" (from LIRMM) (see Figure 4a). Thus, the characteristics of ROVs are as follows:

- They are generally over-actuated.

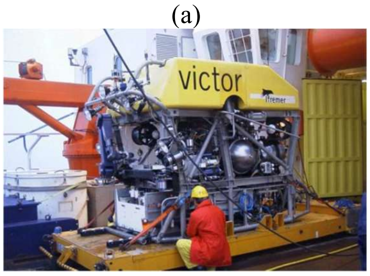
- They have the ability to park at a fixed point.

- They are connected to the surface by an umbilical.

In most models, they are also equipped with cameras and sometimes manipulator arms, giving them a great ability to manipulate objects. So, they can perform complex operations like:

- maintenance of underwater structures: the ROV H2000 from Eca-Hytec, equipped with 2 manipulator arms, is able to change parts.
- in-depth inspections (1000m) in the offshore industry: ROV Victor 6000 from Ifremer (see figure 4b).
- inspection and demining.

(a)



(b)

Fig.4. Example of a ROV robot. (a) L2ROV, from LIRMM, (b) Victor 6000, from Ifremer.

3.4. AUTONOMOUS UNDERWATER VEHICLES (AUVs)

Unlike ROVs, these vehicles do not have a connection cable and they carry their own energy. They are designed to perform operations that require a significant degree of autonomy. To avoid a sudden break in the task, the operator can intervene in the decision and control loop through an acoustic link (see Figure 3). Thus, the characteristics of these machines are especially the following:

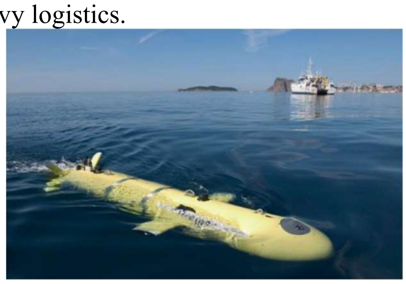
- They are linked to the surface by an acoustic link,
- They embed their own energy as well as their control / command and energy consumption management unit,
- They are generally over-actuated.

AUVs (Autonomous Underwater Vehicles):

An AUV is a robot with a system for locating and navigating to an objective. It is completely autonomous, programmed beforehand to carry out a predefined mission scenario. From a few hundred meters deep, the structure, dimensions and characteristics of AUVs change. AUVs can thus be classified into 2 classes according to the maximum immersion depth reached. We will then talk about coastal AUVs and deep sea AUVs.

Deep sea AUVs: AstrX and IdefX from Ifremer and Daurade from ECA / GESMA (see figures 5b and 5a).

Deep sea AUVs, machines designed to explore the depths of the oceans generally have great energy autonomy, weight and significant dimensions which require rather heavy logistics.



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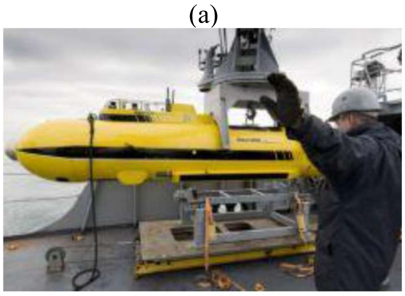


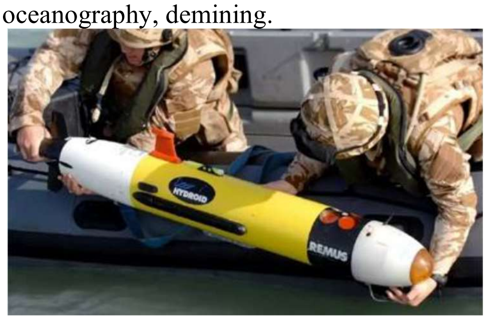
(b)

Fig.5. Examples of deep sea AUV. (a) AstrX and IdefX, Ifremer, (b) Sea bream, ECA/ GESMA

Coastal AUVs: Remus (USA) of Hydroid, Gavia of Hyfmind and Lirmia2 from a collaboration between Lirmm and LAFMIA (see Figures 6b and 6a). Small in size, these vehicles do not require logistics to be implemented. They are completely autonomous and able to determine their absolute position in order to navigate to an objective. They are the essential tool for shallow water missions. The characteristics of coastal AUVs are as follows:

- They are under-actuated.
- They are completely autonomous and the operator cannot intervene in their decision-making.
- They have a privileged axis of movement following the direction of their thruster.

They are generally used in observation missions (video, sonar), measurements, oceanography, demining.



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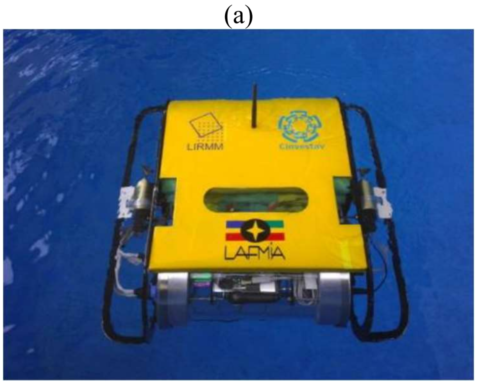


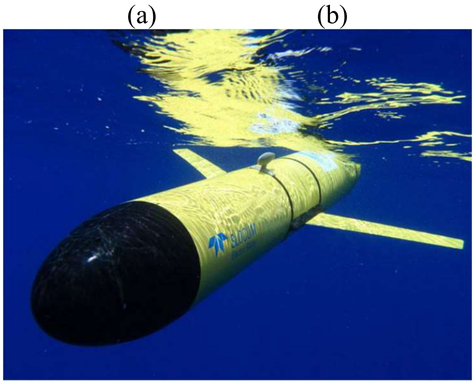
(b)

Fig.6. Examples of coastal AUVs. (a) Remus, hydroid robot camera, (b) Lirmia2, LAFAMIA/LIRMM

- **Underwater gliders (The gliders)**: Slocum glider from Teledyne / WHOI, the 1KA Seaglider from iRobot and SeaExplorer from ACSA (see figures 7c, 7b and 7a).

Generally, gliders are not equipped with an engine. It is an autonomous vehicle, which on the one hand moves by varying its buoyancy which creates a vertical propelling force which produces a relative speed with respect to the fluid. On the other hand, it regulates its direction of navigation by wings and a tackle. The displacement of their internal mass allows them to control themselves in roll and pitch. When the submarine glider is on the surface, the transfer of data acquired during the mission is established. They are used in military missions or in physical oceanography research.

(a) (b)



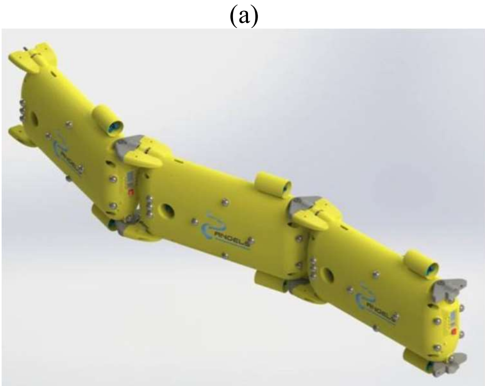
(c)

Fig.7. Examples of submarine gliders. (a) 1KA Seaglider, iRobot, (b) SeaExplorer, ACSA, (c) Slocum glider, Teledyne/WHOI.

- **Biomimetic systems**: The design of these underwater robots is inspired by the dynamics and physical form of marine animals (fish, mollusks) and lead to the emergence of new technologies (Figure 8).

Studies have shown that a design inspired by nature can lead to better efficiency and reduced energy consumption. Examples of specific designs and realizations have emerged as in the case of the flat-fish robot which is inspired by the shape and behavior of a stingray (figure 8b). Another example of biomimetic design is the European Union sponsored Octopus project where octopus tentacle features for propulsion are replicated to obtain a floating vehicle with object handling skills. The Ircynn / EMN robot fish, meanwhile, was designed to detect conductive obstacles by creating an electric field and measuring these deformations (see figure 8b).

(a)



(b)

Fig.8. Examples of biomimetric systems. (a) "flat-fish" (Yamamoto), (b) Angels (IRCCYN / Mines de Nantes)

4. APPLICATIONS OF UNDERWATER ROBOTS

The industrial sector

The industrial and especially energy sector uses the strengths of underwater robots to carry out certain tasks such as:
- inspection of nuclear reactors and hydroelectric dams.
- assistance in the laying of pipelines or cables and the inspection of marine structures.
- the detection and exploitation of the various deposits present in the oceans.

The military sector

An important application of underwater robots is the detection and destruction of underwater mines. Port surveillance is also another rapidly emerging activity; it makes it possible to detect the intrusion of an enemy body (divers or underwater vehicles) in ports. To this end, autonomous robots can be organized in patrols at the entrance to the port. Finally, underwater robots can be used for espionage, minefield detection and delineation, towing monitoring systems and implementing acoustic or electronic countermeasures.

The environment

Underwater robots also have an important role in protecting the environment. They can help identify the different types of pollution (degassing, oil leaks). This is through the inspection of ship hulls for fuel or other leaks. They can also be equipped with biochemical sensors in order to identify the nature and source of the pollutant. In some cases, also, the acquisition of video images with AUVs can allow an estimate of the state of health of preserved natural areas. For the study of climate change, ROVs may have the mission of depositing underwater sensors at the bottom. In particular, the robot can replace humans for autonomous surveillance under ice floes without risking their lives in icy areas.

Scientific applications

Underwater robotics is involved in a wide variety of research projects.

- The study of ocean currents, biological phenomena in the high seas and the main changes in the ecosystem.
- The detection of tsunamis and volcanoes in the ocean.
- Cartography of the seabed.
- Underwater archeology (exploration of wrecks and treasures)
- Flow control and analysis of underwater freshwater sources (amplitude, order of magnitude, salinity)

In a system consisting of a single underwater robot, the frequent applications and the most widespread tasks are (see figure 9):

- Object search (black boxes, leads),
- Monitoring and measurement of magnetic fields in power cables and ship hulls,
- The detection of cracks (dams, preventive safety) and measures (hydrothermal, chemical),
- Checking the health of organisms (algae) and monitoring coral reefs,
- Collection of oceanographic data.

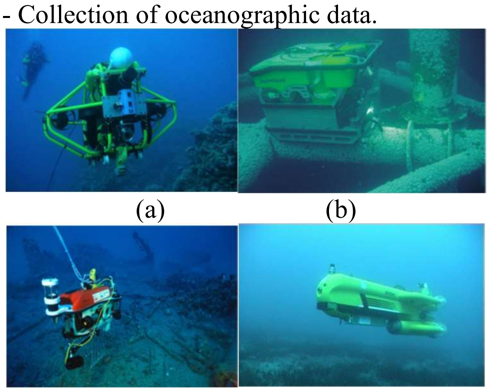


Fig.9. Frequent underwater tasks, (a) checking algae health, (b) detecting cracks, (c) exploring wrecks, (d) detecting objects on the seabed.

5. TECHNICAL ASPECTS OF AN AUV INSPECTION VEHICLE

The exploitation facilities (platform, wellhead, pipeline,...) of offshore oil fields located on the high seas are constantly monitored. Although crucial for safety reasons, it is difficult to achieve due to the hostility of the marine environment and the great depths making human intervention unrealistic. The use of an underwater drone is naturally required. The design of such a machine is essentially based on the type of mission to be carried out. In the particular case of a pipeline inspection, he must be able, in complete autonomy, to locate and then follow the route of the latter over several tens of kilometers in order to check its general condition by focusing attention mainly on the risks. covering with sediments and on areas where the pipeline no longer rests on the supports. He must also be able to check the anchor points of the pipeline.

5.1. PRESENTATION OF THE DRONE

The autonomous inspection submarine, the subject of this article, is developed by the company ECA, located in Toulon (Var), specialized in terrestrial and underwater robotics for hostile environments where humans cannot intervene directly. It offers a wide range of products, in particular in the fields of defense, nuclear and offshore oil.

Fig.10. The ALISTAR autonomous inspection submarine

The ALISTAR 3000 (figure 10) is an autonomous underwater vehicle that falls into the category of "AUV" (Autonomous Underwater Vehicle) capable of performing a wide variety of inspection tasks on offshore oil fields up to a depth of 3000 m. Once the inspection mission has been established and programmed, it offers the possibility of collecting video (camera) and sonar data (lateral and scanning) from the underwater installations visited (pipeline, wellhead,...). It stores this information for later analysis on land. For this study, the profile of a typical mission (Figure 11) of this submarine is broken down by the temporal sequence of five distinct phases:

1. a phase of weighing and preparing the submarine, launching;
2. a descent phase in order to reach the starting point of its inspection work;
3. an inspection phase (checking the general condition of the pipeline);
4. a phase of ascent to the surface;
5. a submarine recovery phase.

In the whole of the subject, we will suppose that the AUV evolves only in the plane (O, X_0, Z_0).

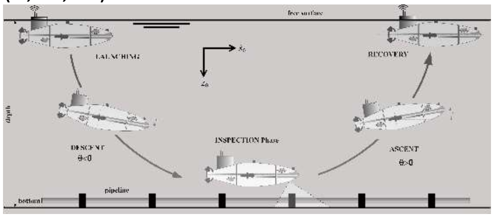


Fig.11. Profile of a typical AUV mission

The AUV environment is described by the inter-actor diagram proposed in partial form in Figure 3. The statements of the identified service functions are as follows:

1 – Perform an underwater inspection of a pipeline

2 – Allow transport on a ship and its launch

3 – Master the compatibility of the AUV with the marine environment

5.2. GENERAL ARCHITECTURE OF THE AUV

To move, ALISTAR is equipped with 8 thrusters: 4 rear main thrusters, 2 side thrusters and 2 vertical thrusters (architecture and location figure 12). This structure provides excellent maneuverability in space without having to resort to steerable control surfaces, which consume energy and are inefficient during certain maneuvers or to counteract the effects of sea currents.

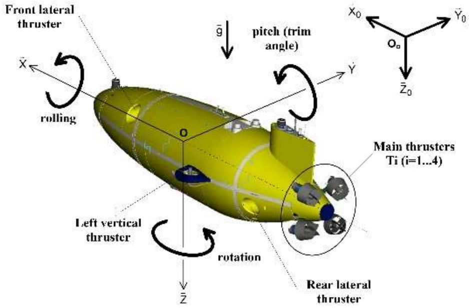


Fig.12. Positioning of the thrusters and angular setting of the AUV

As shown in Figure 13, the AUV can be controlled either by a guidance type agent (automatic piloting in the general case) or even, if possible, by a manual type control (joystick). In the autonomous case, previously defined piloting instructions are provided to the control system as well as feedback information from the various sensors present on the AUV (figure 13). The processing of this data will generate thrust instruction type outputs making it possible to obtain the 6 degrees of freedom of the vehicle necessary for its evolution in three dimensions. The control system activates, according to the control instructions it receives, the control algorithms adapted to the need and ensuring compliance with the constraints imposed by the specifications. The thrust instructions are taken into account by the thrust distributor in order to define the unit control associated with each thruster.

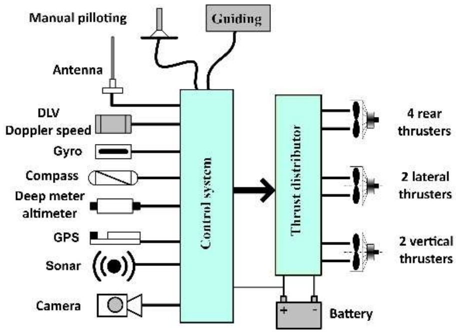


Fig.13. General architecture of the AUV control

The descent and ascent phases are not "useful" phases; they are transitory. The submarine must therefore perform them as quickly as possible while consuming the minimum amount of energy in order to maintain sufficient autonomy for the inspection phase. The development of an Active System for Adjusting the Buoyancy and Trim (SARFA) is part of this perspective. Its goal is to reduce (or ideally eliminate) the use of different thrusters during these transient phases.

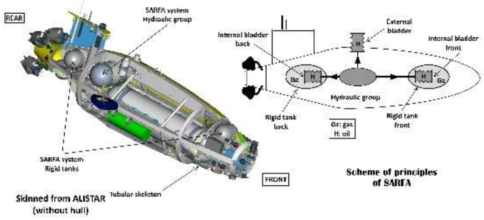


Fig.14. SARFA system

This system consists of a hydraulic unit (electric motor driving a hydraulic pump ensuring the circulation in a closed circuit and under pressure of an incompressible fluid), two rigid reservoirs placed in the median plane (one towards the front and one towards the back of the AUV) filled with a gas and in which we place a bladder of variable volume and finally an external bladder to the AUV. As shown in Figure 14, the pressurized fluid can circulate in the 3 bladders via a distribution module (not shown). Thus conceived, this system makes it possible to perform the two functions of SARFA:

- buoyancy adjustment; this adjustment is made by varying the overall volume of the submarine. The transfer of pressurized hydraulic fluid to the external bladder allows the latter to be inflated, affecting the volume of the AUV and consequently causing a modification of the Archimedean thrust applied to the vehicle;

- adjustment of the trim angle $\theta(t)$ (also called pitch angle); this adjustment is made by unbalancing the masses of hydraulic fluid placed inside the two front and rear bladders. By transferring fluid from one bladder to the other, it becomes possible to change the trim angle independent of the buoyancy setting. Basically, by this operation, we move the center of gravity G of the machine.

5. CONCLUDING REMARKS

This article first gave us a general idea of underwater robotics and its applications. Then was presented the architecture of an Autonomous Underwater Vehicle capable of performing a wide variety of inspection tasks on offshore oil fields up as well as its base functions and movements assisted with an Active System for Adjusting the Buoyancy and Trim (SARFA).

The latest innovations have enabled great advances in this field. New AUV launches, big results or even records like the World Record for the continuous underwater navigation distance of an AUV (317 kilometers in 56 hours without interruption at 800 meters depth) propel new types of sub -autonomous sailors. These new drones now set off to conquer the seabed, to go and work alone, with nothing that connects them to the surface in inaccessible areas.

Technological developments and increasing robotization have contributed to improving man intervention capabilities under the sea. As in space, the question of the place of man in the environment continues to arise. The use of AUVs during the night to prepare a Nautile dive the following day is thus often practiced to optimize the organization of oceanographic campaigns. For long or repetitive operations, robots provide a major gain in terms of capacity and productivity. In some ways, the exploration of the oceans means conquering or controlling its resources by man. Scientific research and geostrategic and economic interests juxtapose, even coexist. There is in this area the syndrome of "planting a flag", "human marking", much more symbolic when the man is as close as possible to the environment. The renewed interest of large emerging countries in manned deep submersibles illustrates this aspect more and more strongly in a context of intense competition on an international scale.

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Paper received on October 30th, 2020

