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ABOUT UNDERWATER ROBOTS AND THEIR APPLICATION IN HYPERBARIC WELDING

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ABSTRACT

Seabeds remain largely mysterious. However, their exploration and exploitation constitute major stakes for the future of our planet. The exploitation of their natural resources (fisheries and biological resources, minerals, oil and gas) and the study of their influence on the climate are unavoidable challenges if we want to offer a future to forthcoming generations. Advances in underwater robotics make it possible to envisage better knowledge and exploitation of this environment still inaccessible to humans. This article presents the current state of technology in underwater robotics and its civilian applications (current and affordable in the near future) mainly for autonomous and hyperbaric welding robots.

Keywords: robotics, underwater, hyperbaric welding, welding parameters

1. INTRODUCTION

While they occupy 70% of the planet's surface, seas and oceans are still largely unknown, while their exploration remains a major challenge for the future. One can be surprised that while scientific progress has allowed man to conquer space since 60 years ago, our knowledge of the underwater environment remains imperfect. It is necessary to look for the reason for the two difficulties that are encountered when we want to undertake the exploration of this environment: the pressures, which quickly become extreme, and the difficulty in transmitting communications in the aquatic environment.

The challenge posed by the exploration of the oceans has increased over the last decades due to the scarcity of terrestrial resources (minerals, oil), the opportunity to access new food resources and, finally, at a time when we are talking more and more about the warming of the planet, about the still little-known interaction between the oceans and the climate and energy recovery.

2. BRIEF HISTORY

It is the military who first tried to conquer this space with the development of submarines, inhabited and armed, offering the possibility to move in total discretion and to intervene by surprise.

Over the past fifty years, underwater applications have expanded and they can be classified into three main categories: military applications, which are interested in relatively shallow depths (300 m), scientific applications of oceanology and, more recently, the exploitation of offshore resources and raw materials. These last two categories are interested in much more important depths (from 4,000 to 6,000 m, even more; it is commonly accepted that the deepest site is the Mariana Trough, in the Pacific Ocean, with a depth of around 11,000 m). In addition to these major categories of applications, which represent obvious economic challenges, there is the search for wrecks and damaged objects at sea (the most publicized example being the search for the black boxes of aircraft lost at sea, such as those of the flight AF 447 Rio-Paris, found in May 2011 after two years of fruitless attempts).

3. THE UNDERWATER ROBOT, AN EXPLORATION TOOL

How to explore such large expanses in such a hostile environment? How to exploit deposits under several hundred bars of pressure, when a man cannot access them? The answer to both questions is the underwater robot. The idea is not new: as early as the 1970s, remotely operated robots made it possible to destroy underwater mines without exposing human lives, and in the mid-1980s, the Killer Whale (see Fig. 1), an autonomous robot developed by ECA, explored the wreck of the Titanic liner, stranded at a depth of 3,800 m, in the North Atlantic.

Fig.1. The Killer Whale (Source: ECA)

The evolution of technology, over the last twenty years, has made it possible to develop increasingly sophisticated underwater robots that are increasingly endowed with decision-making autonomy enabling them to overcome any transmission of information with the surface.

There are two types of these robots: the oldest, ROVs (Remote Operated Vehicles) (or remotely operated) and, more recently, AUVs (Autonomous Underwater Vehicles). ROVs have a limited range because they are connected to the surface by an umbilical cable carrying their energy and allowing high-speed communication with an operator. They are most often used to explore a limited area and are capable of carrying out underwater interventions using electric or hydraulic manipulator arms (these are the so-called Work-Class ROVs). They are used for underwater work on offshore oil fields, for recovery operations (see Fig. 2) or for inspection operations that do not require a large radius of action.

Fig.2. The ROV Victor 6000 (Source: ECA/ Ifremer)

AUVs are much more complex since, not being linked to the surface, they must have energy autonomy and decision-making autonomy, enabling them to accomplish their mission, whatever the circumstances (currents, obstacles …). On the other hand, they have ranges of up to several tens of nautical miles and are particularly suitable for inspection or surveillance missions over large areas.

Therefore, ROVs and AUVs are complementary tools. Thus, it was the successive use of these two types of robots that made it possible to find the black boxes of Air-

France flight 447. During phase 4 of the search, an area of 10,000 km² was explored by three AUV Remus 6000 (from the company Kongsberg). After a week of exploration, one of the mobilized AUVs was able to detect the debris from the fuselage of the A330 lost at sea. A Remora 6000 ROV (built by Phoenix Int') was then able to intervene and recover the flight recorders.

An underwater robot is more or less a complex system comprising of an underwater vehicle (consisting of a hull, thrusters, navigation and localization systems, guidance, energy management, communication), a payload composed of sensors (cameras, sonars, echo sounders, magnetometers, etc.) and actuators (for ROVs) and, where applicable, information preprocessing and storage systems, a mechanical launch system and recovery (which can be sophisticated if the robot has to be launched and/or recovered in heavy seas) and, finally, a ground station (mission preparation, data processing and post-processing, piloting station (for ROVs)).

3.1. ROVs

As mentioned above, ROVs are characterized by the umbilical cable (or more simply "the umbilical") which connects them to their pilot station. This umbilical has the essential function of transmitting the signals necessary for the remote operation of the vehicle (control of the various thrusters which makes it possible to move and orient the robot), as well as the signals coming from the sensors (cameras or sonars) and, finally, orders to the actuators (projectors and manipulator's arms). Figure 3 represents an intervention ROV used by the French Navy for research operations up to 1000 meters deep.

This umbilical has the possibility to convey electrical energy when significant powers are necessary to carry out the mission. In a certain number of cases, however, ROVs can be self-sufficient in energy thanks to batteries on board the vehicle (we then speak of hybrid ROVs). However, this configuration only concerns robots, the mission of which is limited either to observation or to short-term missions.

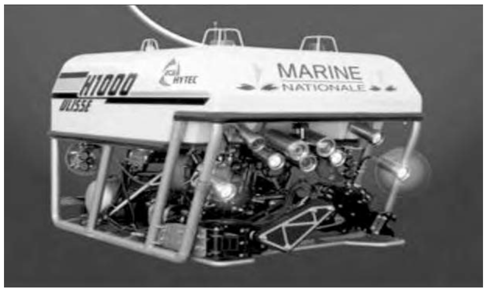

Fig.3. The ROV 1000, intervention robot of the French Navy (Source: ECA)

The depth of intervention is decisive in the choice of technologies used. In depths of several thousand meters, the constraints require different elements to be placed under equal pressure in order to avoid the risk of leaks and crushing. For operations on shoals (down to -300 m), more conventional technologies are used.

One of the defining characteristics of ROVs is also the power required to perform underwater work. Thus, in deep seas and to carry out interventions on underwater structures (especially in the field of offshore oil), hydraulic manipulator arms will be preferred.

This ability to carry out underwater work constitutes the whole point of these robots, with, however, a limitation of their range of action and implementation constraints, due to an umbilical whose length can reach several kilometers and which can therefore be subjected to significant forces due to its own weight and the presence of currents (see Fig. 3).

3.2. AUVs

In order to overcome these limitations, autonomous underwater robots (AUV: Autonomous Underwater Vehicles) have emerged. No longer connected to the surface, the mechanical stresses disappear. The disadvantages of this advantage are as follows: the electrical energy must be on-board, but the storage capacities limit the autonomy, all the more so as the consumption of the on-board equipment is high; it is also necessary to carry a navigation system and decision-making autonomy equipment (inertial navigation unit, device for resetting surface position by GPS, navigation and guidance computer on a trajectory, automatic avoidance systems for obstacles, etc.) and, finally, almost non-existent communication between the surface and the robot when it is diving. Fig. 4 shows an inspection AUV used by the offshore extractive industry.

Fig.4. The Alistar-3000, inspection AUV - usable up to 3,000 m deep (Source: ECA)

Current electronic and computer technologies provide solutions to these various drawbacks. Today, there are precise and miniaturized inertial units; the processing capacities make it possible to embed complex software implementing techniques relating to artificial intelligence; sonars, often from military technologies, that provide precise data on the robot's environment.

The impossibility of real-time communications is linked to the aquatic environment. Indeed, only acoustic waves propagate in water (and even then, with great limitations). The transmission rates remain low (a few kbits/sec), which at best only allows system states or basic orders to be transmitted, but in no case images or data streams. On the other hand, when the robot has risen to the surface, radio communications become possible again and make it possible to retrieve data or download new mission plans.

Energy storage capacities constitute a second limitation. Despite technological progress, particularly with lithium-ion batteries, the proliferation of on-board systems increases electricity consumption and energy management systems that are necessary to ensure autonomy, often required, ranging from 10 to 15 hours. This energy management consists of a coupling to the navigation system, making it possible to optimize the trajectories according to the sea currents and to minimize the consumption of the thrusters, as well as an intelligent system of starting (or putting on standby) the different equipment, according to the various phases of the mission.

Experiments have been carried out with fuel cells, but they are not conclusive, at this stage, for operational uses.

Limited communications and power constraints restrict the use of AUVs for inspection and surveillance missions. These do not have the capacity to carry out underwater work requiring manipulation.

3.3. SONAR, THE KEY SENSOR OF THE UNDERWATER ROBOT

Most early underwater robots were equipped with cameras, and these are still the most commonly used sensors for ROVs today. However, the cameras can only be used near the objects to be observed or to work on. The turbidity of the waters and the absence of light (the range of projectors remains limited to a few tens of centimeters) considerably limit their usefulness. It is therefore the sonar (ultrasonic detector) that is the most suitable sensor for remote "vision", in an almost opaque environment. Like a radar, sonar makes it possible to designate a target, "hang on" it and follow it.

Fig.5. Image of plane wreckage obtained by post-processing of sonar signals (Source: ECA/ Triton Imaging Inc.)

Sonar technology has evolved considerably, making it possible to obtain very high-performance resolutions and very low false alarm probabilities. Specific technologies have been developed depending on the type of measurement to be performed (Side Scan, Multibeam Echosounder, etc.). Similarly, on the most efficient sonars, "synthetic antennas" have replaced mechanical scanning. Signal processing software is also becoming more and more efficient. They allow the display of extremely precise underwater images of a quality comparable to that of a photograph (see Fig. 5 above).

You no longer need to be an underwater acoustics specialist to interpret a sonar image. Figure 5 is an illustration of this: it shows the acoustic image of an airplane wreckage (after post-processing).

4. CIVIL APPLICATIONS

The applications of underwater robotics are numerous (we have already mentioned a few). In the field of offshore oil, ROVs are used to carry out underwater work such as interventions on wellheads, repairs, plugging, etc. The disaster at the British Petroleum production platform last year, in the Gulf of Mexico, showed the complexity of responding to such accidents. The applications of AUVs to this economic sector are still limited, but they are developing, in particular with the inspection and monitoring of subsea pipeline networks (for example, measurement of anomalies with the aim of preventing environmental disasters), or even with the help in laying pipelines by characterizing the contact point and checking that the pipeline has indeed been laid in the planned furrow.

In the field of oceanography and hydrography, AUVs are used to perform various measurements or to map the seabed. Thus, the SHOM (Hydrographic and Oceanographic Service of the Navy) has an AUV, called Daurade, which is dedicated to REA (Rapid Environmental Assessment) missions (see Fig. 6 below).

Fig.6. Image The AUV Daurade by SHOM (Source: ECA)

It is the field of civil security that undoubtedly contributes the most to the media coverage of these new technologies. The search for wrecks, damaged aircraft at sea and their flight recorders are the best known aspects of this (as we have already mentioned in connection with the search for the black boxes of flight AF 447 Rio-Paris or more about the air disaster in Sharm El-Sheikh, Egypt). However, other applications have emerged, for example, the National Gendarmerie frequently uses a ROV when searching (in bodies of water) for missing persons, and EDF uses small ROVs to inspect the pools of its nuclear reactors and its hydraulic dams, in order to verify the absence of anomalies.

Fig.7. The ROV Roving Bat (Source: ECA)

At ECA, it was developed a very special ROV, the Rovingbat (see Fig. 7) that is capable of pressing against the hull of a ship and moving around it (thanks to tracks) in order to carry out very diverse missions and thus avoid having to resort to divers. This is the case with the inspection of hulls to measure corrosion or detect the presence of explosive devices or, more simply, the cleaning of concretions to avoid dry docking.

In the following, a few words about the military applications that finance a good part of the R&D necessary for the development of these robots. The oldest use is that of mine warfare. Many underwater mines have been (and still are) laid by the States to protect or prevent access to sensitive areas: ports, military installations, access channels, sea passages. The most modern mines, reacting to acoustic or magnetic signatures of ships, are not very accessible to dredging techniques. More than forty years ago, the idea was born to send robots to neutralize them. One of the first of these robots to be used was the PAP (Poisson Self-propelled Piloté) developed by ECA in the early 1980s (see Fig. 8).

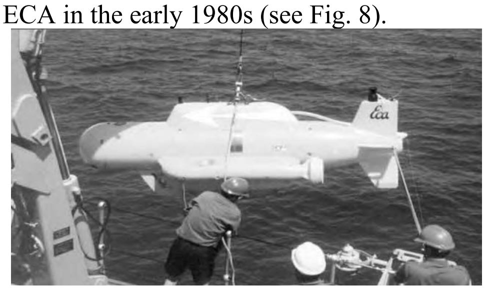

Fig.8. The PAP, implemented on a mine-hunting vessel (Source: ECA)

This teleoperated robot thanks to a coaxial link (then fiber optic) with a mine-hunting ship deposited an explosive charge near the mine to be neutralized. The remote firing of this charge neutralized the mine by influence, and therefore did not expose the lives of clearance divers. Nearly 500 copies of the PAP have been sold and have been used by many navies around the world. Some continue to operate it. Since then, the technology has evolved, with the concepts of Mine Killers, "kamikaze" robots that use the same principle, except that they explode with the mine (see Fig. 9). On the other hand, they are more manageable and less expensive.

The location of mines has also progressed. Traditional localization, from a hull sonar or a towed sonar, has the disadvantage of exposing a ship.

Fig.9. The K Ster mine-killer (Source: ECA)

The use of AUVs, alone or in cooperation with an USV (Unmanned Surface Vehicle), is a new concept that is developing today. This is the subject of the Espadon upstream study plan, conducted by the Direction Générale de l'Armement (DGA) and carried out in cooperation between the DCNS group, Thales Underwater Systems, and ECA with a view to validate these innovative concepts.

These studies (carried out in France, but also in other countries) make it possible to make considerable progress in the implemented technologies: sonars, energy, propulsion, autonomous navigation, etc. These are typically dual technologies. The benefits in the civilian field concern all the applications already mentioned, and there are probably still many more others to imagine.

5. HYPERBARIC WELDING ROBOT

The HYDRA IV experiment (November 1983) has enabled us to successfully identify the narcotic limits of the "deepest gas": hydrogen. Everything suggests that complex operations performed by divers will be possible up to 600 meters in a relatively short time, using helium-hydrogen and oxygen cocktails. If the diver can do the job, what is the use of mobilizing such energy around underwater robotics? The answer is simple and can be summed up in one word: competitiveness.

The life and work of divers in deep waters require the use of specialized equipment and support vessels, the complexity and cost of which are disproportionate to the simplicity of the underwater tasks to be performed: observation, measuring, cutting, welding, cleaning, etc. Thus, the reduction of operation costs at sea begins with the reduction or - even for the most basic tasks - by eliminating the working time of deep divers.

Indeed, the end of the 1980s has seen the development of fields located in difficult and deep waters like OSBERG and TROLL for the Norwegian zone alone. To work in these areas and remain competitive, underwater operators will need to use robotics. The connection of pipes by welding represents a sensitive link in the construction chain. The installations of these often large fields will have to have a service life of at least 20 years and will most likely require welded pipe connections. The increase in the speed of welding by an automatic machine should enable to save one to three days of operation.

Security and reliability should also find their account a priori, a machine does not breathe and has no state of mind.

In fact, two orientations are possible to solve or circumvent the problem of the variation of the profiles of chamfers.

First of all, we can partially circumvent the problem by improving the alignment, the machining of the ends of the tube as well as the metrology of the sleeve.

Despite everything, it seems realistic to believe that any subsea preparation carried out on subsea pipes without internal clamping will never reach the quality of those carried out in the factory.

To solve this problem of variation in bevel profiles, the machine will have to adapt its welding parameters and the movements of its torch to these variations.

We will indeed be dealing with an "intelligent" welding machine, in other words, a "robot". This development requires two ambitious sub-programs:

a) A bevel recognition and metrology system capable of operating in real-time and close to the welding arc;

b) The creation of a database of welding parameters, torch kinematics, functions of depth, type of steel, an orbital position of the torch, and especially the geometry of the bevels.

The realization of these two sub-programs will allow the robot to adapt in a closed or semi-closed loop to the imperfections, as well as to the modifications occurring during welding.

Therefore, COMEX launched the development of a shape recognition sensor in 1981, based on the principle of profile segmentation.

It consists of a laser associated with a cylindrical lens generating a plane of light that intercepts the chamfer at 90° measure. The line of light is then captured by a CCD camera located at 45° equipped with a filter centered on the wavelength of the arc.

This image is only an approximation of the cross-section, and this is for two reasons:

• the line of sight of the camera cannot be parallel to the chamfer generators, therefore, the image must be straightened by 45°,

• the light line has a thickness of the order of 1 mm, but the precision required is 0.5 mm.

Therefore, it is necessary to associate with this "raw" sensor an image processing device that identifies the edges of the segments, filters the image noise, scales, and straightens the profile.

First of all, this processing is carried out by a real-time operator, wired said extractor of contour, which itself breaks down into four functional modules:

• the camera interface module performs analog and digital conversion as well as a clock function;

• the gradient operator module extracts the modulus and the orientation of the gradient vector of each pixel;

• the contour operator module identifies the pixels for which the gradient vector passes through a local maximum. In the case of our application, the second contour of the laser line is identified and transmitted to the feature extraction computer;

• finally, a last module allows the visualization of the image gradient modulus.

Such an operator is capable of processing 50 frames per second.

The sensor, thus defined and developed by COMEX, makes it possible to obtain a precision of plus or minus 0.15 mm.

Fig.10. Wet FSW robot for use in ship hull repairs (Source: IGUS)

The prototype was developed to its final hyperbaric version:

• use of laser diodes and optical fibers,

• decomposition of the CCD camera,

• use of a fiber optic endoscope,

• processor optimization.

This will allow us to have precise data concerning the characteristics of the chamfers.

To adapt the movements of the torch, the welding parameters, and the bevel variations, it is of course important to know the functions linking all these variables.

6. CONCLUDING REMARKS

The underwater robots market is a niche market, in which the number of players is limited. Nevertheless, it is the Europeans who are the most present in this sector because of the oil fields in the North Sea, and also because, in the military field, the European navies have been made aware (since the Second World War) of the problems of mine clearance in their coastal areas.

The manufacturers of underwater robots are either systems manufacturers who have developed such equipment to meet their own needs (Kongsberg, SAAB, Bae, or STN Atlas) or companies specialized in robotics technologies (ECA, with a wide range of AUVs, USVs, ROVs, Minekillers, but also land robots, ISE - AUVs and ROVs, Hafmynd) or a few manufacturers only specialized in the manufacture of ROVs for civil use.

Alongside these few manufacturers, major customers are advancing the technology either by financing development programs for demonstrators (DGA in France) or because they themselves are users and they have R&D teams that bring out new concepts (Ifremer).

End users have already been mentioned above, for the most part. However, it should be mentioned, in the offshore oil industry sector, the role of service companies (Technip, Bourbon, Oceaneering), which invest in this type of equipment to provide their services for the benefit of the oil companies, which rather play the role of prescriber in this area.

This market is far from having reached maturity, so it is difficult to assess it and position the various players. Nevertheless, the global annual volume of the orders is a few tens of millions of euros for ROVs and around 20 to 30 million euros per year for AUVs.

In conclusion, underwater robotics is still in its infancy. But already there are many conceivable applications. The technical problems to be solved to advance this discipline are varied and exciting.

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