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Underwater Robotics: Principles, Components, Modeling, and Control

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ABSTRACT

Underwater robotic systems have profoundly transformed the field of deep-sea exploration, enabling operations in remote subsea installations. The outlook for this technology is highly promising. This study aims to offer an in-depth understanding of the subject matter to postgraduate students, engineers, and researchers with a keen interest in the realm of underwater robotics. Furthermore, this work encompasses a comprehensive survey of the diverse domains within the field of underwater robotics.

Keywords:

Underwater Technology, Robotics Components, Components, Modeling, Control, Field Survey, Remote Operations. Embedded wireless communication.

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1. INTRODUCTION

As is well known, about two-thirds of the Earth's surface is covered by water. The oceans allow the transportation of products and raw materials between countries, represent critical sources of food and other resources such as oil and gas, and have a great effect on the climate and the environment.

Scientific knowledge of the deep seas is growing rapidly through the use of a variety of technologies. The first scientific explorations were carried out using underwater vehicles occupied by humans. Recently, underwater robots have begun to revolutionize seafloor exploration, generally offering better information at a lower cost. On the other hand, these robots have made it possible to carry out operations in deep waters, and also to intervene in disasters such as leaks in oil facilities. The history of underwater robots begins in the early 1950s with the construction of a remotely operated underwater robot named POODLE developed by Dimitri Rebikoff in France. Since then several teleoperated and autonomous underwater robots have been developed [1].

The purpose of this text is, on the one hand, to serve as a first contact with the topic of underwater robotics, and on the other hand, to present a review of the state of the art on different aspects of this area of robotics. In this section, a classification of underwater robots is made and their applications are described. In section 2, the types of components that are commonly found in underwater robots (the cabin, sensors, propulsion system, etc.) are presented. Later, in section 3, the kinematic and dynamic modeling of these robots is presented. The derivation of the equations of motion is briefly explained. Special emphasis is placed on this section because in underwater robots the speed and its temporal derivative are measured with respect to the body's reference frame. In section 4 a review of the control strategies that have been proposed for underwater robots is carried out. Finally, in section 5 the conclusions are presented and some 'useful references' to consult are cited.

1.1 Classification of Underwater Robots

Underwater robots can be classified by their level of autonomy, the type of mission to be carried out, and their propulsion system.

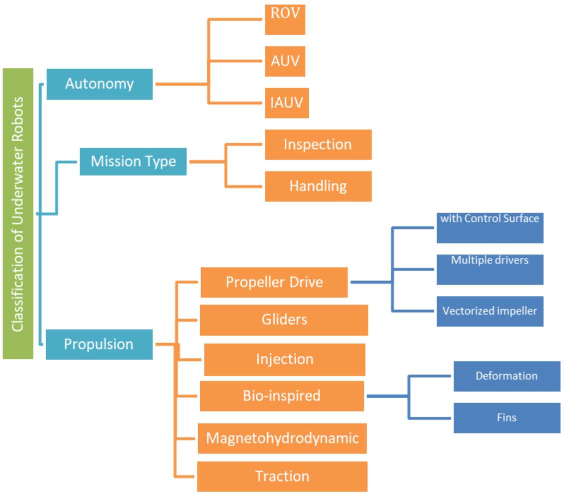


Fig. 1: Classification of underwater robots.

In Fig. 1 it can be noticed that a classification of underwater robots. The main way to classify them is according to their level of autonomy. There are completely autonomous robots and others that must be continuously controlled by an operator; these are AUVs and ROVs, respectively. On the other hand, there are the IAUVs, which can currently be considered at an intermediate level of autonomy, since the prototypes developed so far require Supervised Control or an operator who performs the reasoning task to determine the actions that must be carried out to complete the mission [2].

However, the final objective of these robots is for them to become completely autonomous and it is only the operator who initially defines the mission to be carried out through high-level commands. On the other hand, these robots can be classified by the type of mission to be carried out. Missions can be inspection (or observation) or manipulation (or intervention). The main difference between a robot designed to perform interventions and another that only performs inspections is that the former must have tools or a robotic arm.

The mission for whom an underwater robot is designed will define the type of sensors, actuators, and structure it should have. The propulsion system of an underwater robot completely defines the types of movements and maneuvers that it can perform.

Propulsion systems also have implications for energy consumption, robot hardware, and the effect that the robot generates on the marine environment. The main propulsion systems are; Propeller Drives, Aquatic Gliders (based on Ballast and Fin Systems), and Bio-inspired Systems. In the experimental phase or whose technology has not fully matured are those based on Water Injection and Magneto- hydrodynamics. Another propulsion system is Traction. This can be with the seabed or with other surfaces such as the hull of a boat.

1.2. Applications of underwater robberies

An underwater robot is designed to perform tasks underwater; these can be performed while sailing or upon reaching a predetermined location using some type of manipulator. From this point of view, underwater robots can do two types of missions:

Inspection Missions. These are those missions that are carried out during the navigation of the underwater robot. In this type of tasks, a manipulating arm or mechanisms to interact with the environment are not required. An inspection mission may consist of: acquiring images with one or more cameras, while the robot navigates in the water; the observation of the seabed, by obtaining data from acoustic cartography or water quality, and the review of underwater installations, such as metal structures, pipelines, cables, etc.

Manipulation Missions. They are those missions in which the underwater robot intervenes manipulator arms or tools. To carry out these missions, a real-time vision system must be available (in the case of ROVs), which provides the operator with live images of the operating environment. Typical handling tasks include; the maintenance of underwater structures, the opening and closing of valves in underwater installations, the deactivation of mines, the assembly and disassembly of components, the collection of samples for archaeological, geological, or ecological studies, intervention in disasters to control leaks of contaminating material or support in the rescue of people [2,3,4,5].

1.3. Remotely Operated Underwater Robots :(ROVs)

Remotely operated underwater robots (ROVs) are linked to the surface through an umbilical cord, comprising a set of connected cables that facilitate both data exchange and the provision of energy to the robot. Users define commands for the robot through the graphical interface of a computer situated on the surface, the user defines the commands that the robot should execute. In turn, the ROV sends the signals from its sensors (pressure, temperature, images, etc.) to the computer on the surface, so that the user knows the state of the robot and the environment that surrounds it [2].

Currently, oil or gas facilities are served by ROVs. The demands of work performed on subsea structures are high, requiring frequent inspection and intervention to perform drilling operations, manipulate valves, repair or replace subsea components, and perform a variety of tasks required to maintain the pace of production and product quality. The trend in the use of ROVs will increase as oil and gas production in near-shore facilities move to deeper waters [6].

When tasks are carried out at great depths, the drag forces exerted on the surface of the cable are greater. This makes the vehicle less manageable. Although the cables have increased their diameter (due to greater energy requirements), the increase in the surface area of incidence of the drag forces is a product, to a large extent, of their extensive length. However, some solutions have been presented, such as building a Tether-Cable Management System (TMS) that is anchored to the seabed and supports the drag forces of the longest distance cable (the one that goes from the surface vessel to the TMS) and at the same time allows the ROV to navigate more easily [7]

1.4. Autonomous Underwater vehicle: (AUVs)

Autonomous underwater vehicles (AUVs) have a control architecture that allows them to perform missions without the supervision of an operator. In addition, they contain their own energy source, generally based on rechargeable batteries. Generally, there is no line of communication between the vehicle and the surface since it is usually programmed with predefined tasks and missions. However, when an exchange of information with the surface is required, communication can be carried out through acoustic devices. These robots can solve the limitations imposed by ROV cables for some tasks. AUVs are currently used for scientific exploration, oceanographic sampling, underwater archeology [8], and under-ice exploration. The data collected by the vehicle is stored in its internal memory to later be analyzed [9].

On the other hand, they have also been used for military operations (e.g. mine detection), and more elaborate applications are being developed, such as underwater surveillance. By 2008, it was estimated that around 200 AUVs were in operation, many of them experimentally [10] However, this technology is maturing rapidly and some companies already offer services with this type of robots [11].

1.5. Autonomous Underwater Robots for Interventions: (IAUVs)

AUVs have been designed to carry out observation missions; however, recently there has been interest in them being able to perform manipulation tasks. This is the idea behind autonomous underwater intervention robots (IAUVs). With these types of robots, the missions would be more economical than in the case of ROVs, in addition their maneuverability would be superior since the IAUV would be free of the restrictions imposed by the umbilical cord.

Examples of developments of this type of robots are the ALIVE projects [12], SAUVIM [13], and RAUVI [14]. The ALIVE vehicle navigates autonomously to the place where the intervention will be carried out. Once it reaches the desired position, it changes its operation to Supervised Control and, through acoustic communication, performs the manipulation tasks. For its part, the GIRONA 500 robot (from the RAUVI project) first explores the region of interest and takes acoustic and visual information from the bottom. Subsequently, the robot rises to the surface where the collected information is processed to perform a reconstruction of the explored region. Through a graphical user interface, an operator identifies the object of interest and gives commands to the robot to carry out the intervention. To date, experimental tests have been successfully carried out in a scenario in which the robot's mission was to recover an airplane black box [15].

2. COMPONENTS OF UNDERWATER ROBOTS

2.1. The cabin

The cabin (hull) consists of the structure and the material that covers the underwater robot. The on-board computer, the electrical and electronic equipment (electric motors, controllers, signal converters, sensors, electronic cards, etc.), and the mechanical elements of the robot (such as the control system) are mounted and/or contained in the cabin. Ballast, fins and, impellers) [16].

The factors that determine the design of a cabin are the depth at which it will operate (and therefore the hydrostatic pressure it will withstand), the temperature levels it will resist, the resistance to corrosion, the volume of the elements it will contain, the ease of assembly/disassembly; the feasibility of its construction and the cost.

On the other hand, another factor that must be considered is the drag forces generated by the movement of the robot. These forces are proportional to the square of the robot's speed. When the robot moves at a constant speed, the force generated by the impeller is equal to the drag forces. Therefore, the lower the drag forces, the lower the energy consumed during the robot's navigation. Drag forces depend largely on the geometry of the cabin.

In AUV design, a cylindrical cockpit is a very popular choice. This is because (for a given robot volume) the drag forces generated are small when compared to other geometries. On the other hand, this geometric shape is suitable for resisting the hydrostatic pressure generated at great depths [18]. Furthermore, the manufacture of a cabin with this geometry is relatively simple and this in turn has favorable consequences on cost. It should be noted that the external shape of the vehicle is not necessarily that of the compartments that house the electrical and electronic equipment. on the other hand, to counteract the hydrostatic pressure, the cabin is often flooded with oil.

Table 1: Materials for cabins, extracted from [17].

Material	Density (kg/dm 3)	Yield strength (MPa)	tensile Module (GPa)	Specific strength (kNm/kg)
High Strength steel (HY 80)	7.86	550	207	70
aluminum alloy (7075-6)	173	503	70	173
titanium alloy (6-4 stoa)	184	830	120	184
GFRP (epoxy/s-lass)	2.1	1200	65	571
MMC (6061 AL/Sic)	1.7	1200	210	706
Acrylic	1.2	103	3.1	86
PVC	1.4	48	35	34

An elementary part of the cabin design is the shape of the front end. A flat front end is not advisable for a robot that will perform tasks at high speeds, since the phenomenon called cavitation takes place on the edges of the front face, which can cause erosion or rupture of the cabin material. In [19] the use of an oval end is advised to reduce cavitation and drag forces on the robot.

Another important aspect of cabin design is the type of material. In [20] a discussion is presented about the different types of materials mostly used in the construction of underwater robots. These materials are mainly metallic, composites, and plastics. Table 1 shows the properties of some materials used in the construction of cabins.

A desired characteristic of the material to be used is that it is highly resistant and light in weight. Composite materials show better properties than metallic materials and plastics; this can be seen in table 1. In the design of underwater robots, the composite materials used are plastics reinforced with glass fiber (GFRP) and carbon fiber (CFRP). Fiberglass-reinforced plastic is the most used because it is the most economical [20]. of the metals considered, titanium has the highest strength/weight ratio, followed by aluminum and steel. However, the cost of titanium is higher than the rest. Aluminum has a better strength/weight ratio than steel and its price is affordable. Aluminum cabins must be suitably anodized and provided with punishing anodes to avoid corrosion.

Acrylic is used in underwater vehicles that operate at depths of up to 1 kilometer. It is a transparent and highly resistant material. It is used in the windows that allow video cameras to see objects of interest. PVC is an inexpensive material that can be used to build underwater vehicles that will work at shallow depths [21].

2.2. Sensors

Underwater robots are equipped with sensor systems dedicated to determining the location of the vehicle, its speed and acceleration, as well as its operating status [22]. Vision systems fall into this category of devices when they are used to determine the position and orientation of objects with respect to the vehicle. The sensors allow the robot's movements to be controlled, which in turn allows it to carry out the mission entrusted to it. They can be classified as:

- ***Positioning.***
- ***Internal state.***
- ***Environmental measurement.***

This section presents only Positioning sensors and internal state sensors. Environmental measurement sensors are those that are used to determine the characteristics of the water that surrounds them, some of these measure the following variables: conductivity, pH, density, turbidity, dissolved oxygen, temperature, presence of metals, etc.

Another very important type of device, used to characterize the seabed, is Sonar. This device consists of one or more emitters (called acoustic projectors) and one or more receivers (called hydrophones). As there is a transmission of the acoustic ultrasonic signal, the distance of the detected objects is determined, according to the speed and time traveled by the sound in the water. Sonars can be used to estimate the distance to an object (e.g. icebergs, enemy submarines, etc.), generate images of the seabed (for underwater archeology), and make bathymetric maps [23].

2.2.1. Positioning Sensors

Positioning sensors are those that allow determining the position, orientation, speed, and acceleration of the underwater robot concerning an inertial reference frame or other objects of interest. Below are some of the sensors used by most underwater robots.

Global Positioning System (GPS) allows us to determine the position of an object anywhere in the world. These are used in vessels that support the mission of an ROV or in aquatic gliders to locate themselves once they emerge to the surface of the sea. It cannot be used underwater [24].

Inertial Measurement Unit (IMU). provides information about the vehicle's linear acceleration and angular velocity. The IMU used in underwater robots is based on three gyroscopes that allow measurements of the angles of pitch, roll, and yaw, and then transmit them to other equipment through a communication channel. Currently, IMUs are small ones that integrate gyroscopes and accelerometers in the electronic, there are even some that have compass electronics [25,26].

Solid State Compass. (SSC). A solid-state compass is based on the detection of the Earth's magnetic fields. to do this, it uses two or three magneto-resistors or Hall effect sensors placed at 90º between them, which through a vector calculation determines the north or horizontal reference position. Magnetic compasses can provide estimates of magnetic north with an accuracy of 1º if they are carefully calibrated to compensate for vehicle magnetic disturbances [27].

Doppler navigation speed. The Doppler speedometer navigation is based on the transmission of three or four ultrasonic waves, with a diagonal direction towards the bottom, slightly inclined to the sides, front and back. The device has a processing circuit that, by analyzing the received echoes and their correlations, calculates the speed, and the position is obtained indirectly by odometry. The operation of the Doppler velometer is limited to a certain level with respect to the seabed [28].

Sonar for obstacle detection. As explained above, sonar is based on various projectors and hydrophone arrays. Depending on the time difference between the emission of the acoustic signal and the echo received, the distance at which an object is in front or at certain angles is determined. To detect obstacles, it is also possible to use laser emitters and their receivers, but these can present problems in very turbid waters [29].

Depth sensor. One method to measure depth consists of placing an absolute pressure sensor whose measurement point is in contact with the water. Because the pressure exerted on the sensor is proportional to the water column multiplied by its density (plus atmospheric pressure), the depth value can be obtained [30].

Acoustic Positioning Systems. Acoustic positioning systems allow the position of the robot to be determined in x-y-z. These systems are based on two devices that receive and emit acoustic signals; these are the transceiver and the transponder. The transceiver is mounted on the underwater robot and the transponders are located in places whose location is known. The transceiver sends an acoustic signal that is received by at least three transponders. The transponders respond to this signal, emitting another acoustic signal (which identifies each one) that the transceiver receives. The distance to each transponder is measured from the time it takes for the acoustic signal to arrive. Through triangulation, the position of the robot is determined. There are three types of acoustic positioning systems (which are differentiated by the distance between them), these are Long Baseline Systems (LBL, for Long-Baseline System), Short Base Systems (SBL, for Short-Baseline System), and Ultra-Short Baseline Systems (USBL, for Ultra Short-Baseline System). In an LBL, the transponders are mounted on the seabed, on the perimeter of the area where the exploration is carried out. For their part, in the SBL and USBL, the transponders are attached to the vessel that supports the mission [31].

Vision Systems. Video cameras are used to obtain images of the place where the ROVs are carrying out the operation or in the AUVs to take photographs or videos of the area being explored. Another application of vision systems is to obtain estimates of relative and sometimes absolute movement using a SLAM-type algorithm. This is useful for performing tasks such as vision monitoring of pipes and control of the position. The technology of optical vision systems is highly developed; this allows obtaining images with high resolution, defined colors, and three-dimensional processing. However, from a certain distance, which will depend on the degree of turbidity of the water, underwater objects are difficult to distinguish. This is why some research work has focused on the search for alternatives to produce underwater images through the use of acoustic waves because sound has less attenuation than light in water [30, 31].

2.2.2. Internal State Sensors

These sensors allow for determining the energy consumption of the robot, a possible flood, the internal temperature of the vehicle, etc. Below is a pair of sensors of this type. Electrical Consumption Measurement. Voltmeters and ammeters are devices that allow us to observe the consumption status of motors and batteries. A voltmeter consists of an analog-to-digital converter and is usually integrated into a microcontroller or digital signal processor. An ammeter consists of a precision resistor in series with the circuit to measure consumption, in order to convert it to voltage. In some cases, the electric current can be determined by means of Hall effect sensors placed near the power cables. This will allow the current consumption in each motor and module of the underwater robot to be determined, in order to calculate the power consumption and manage the energy distribution in an AUV.

Flood Detector. This device informs the operator or the on-board computer if there are problems due to lack of water-tightness in the underwater robot. To detect the entry of water inside there are three types of flood sensors: humidity, conductivity, and optical. Of these, the optical sensor is the most practical, since the humidity sensor reacts with a delay and the conductivity sensor is exposed to the electrical noise of the underwater robot components. The optical detector is based on the placement of a prism with a refractive index similar to that of water in the lower internal part. Its operation consists of emitting an optical signal through an LED, and detecting whether or not there is a reflection within the prism. [32].

2.3. Propulsion systems

Propulsion systems are the devices that allow underwater robots to advance in the aquatic environment. Here, both the elements that generate the forces and those that control the direction of these forces are considered as part of the propulsion system.

Although most underwater robot propulsion systems consist of propeller drives, moving fins for guidance, and ballast systems to perform turning operations, other ways of generating motion have been proposed. inside the water, some of these are described below.

2.3.1. Propeller Drives

The thrust system with propeller and motor is the most used in most underwater robots. It generally consists of an electric motor, to which a propeller is attached. When the propeller rotates, it produces a thrust effect by moving the fluid from front to back, due to the pressure difference produced.

The mathematical models of impellers that have been proposed are only an approximation to describe their behavior since many factors influence such as the shape, diameter, and area of the blades; the area of the duct; the rotation speed of the propeller; the currents in the environment; the density and viscosity of water, etc. Different models have been presented in [33, 34].

Frequently, a simple mathematical model of the impeller is used in which the impeller force is proportional to the square of the angular velocity of the propeller, and in turn, this speed is proportional to the motor voltage. The above is under the assumption that the dynamics of the drivers have time constants much smaller than the dynamics of the vehicles [35].

The benefits offered by the propeller drive have made this propulsion system the most used in underwater robots, however, these devices produce a large amount of noise in the marine environment, which alters aquatic life to a certain extent.[36], which is why other propulsion systems are proposed in the development of certain underwater robots.

Impeller and control surfaces. This type of propulsion system is the one most used in large submarines and AUVs. They use fins or rudders with a single degree of freedom to obtain pitch, turn, and roll movements. This system is very simple, but maneuverability is very limited, especially at low speeds.

Multiple drivers. It is the most used system in ROVs. It consists of placing a certain number of impellers to provide maneuverability to the vehicle in the required degrees of freedom. Although the most important thrusters for executing navigation are placed at the rear or on the sides of the underwater robot, there is no specific rule for their location and orientation. A configuration that can provide six degrees of freedom to an underwater vehicle is the one possessed by the ODIN II robot [37].

This arrangement of the impellers allows the robot to rotate on itself. It is mainly used in manipulation and inspection work due to its precision in positioning and its ability to govern the degrees of freedom independently. Underwater robots that use the impeller arrangement system usually have a compact cubic or spherical shape. The drawback of this configuration is the high energy consumption due to the large number of impellers.

Vector drive is the ability of an underwater robot to orient or position a thruster to control its movement. In underwater robots with a vectored thruster, the thruster is placed at the rear, similar to that of vehicles with a fixed thruster and guiding fins, but in this case the thruster is not fixed, since it can orient yourself. The development of underwater robots with vector drives is relatively recent.

In some research works, the dynamics of this type of vehicle have been analyzed and it has been found that it presents great advantages for navigation and precise guidance [38, 39]. In [40] a vector thruster located at the rear was presented that, through a spherical parallel structure, allows pitch and yaw movements.

On the other hand, in [41] and [42] the SENTRY and Odyssey IV AUVs were presented, respectively. These robots have rotating impellers that allow them to control their forward movements and vertical positioning simultaneously. These robots have been used successfully to explore the seabed.

In [43, 44] the design of an underwater robot was presented whose impeller was attached to the cabin through a Stewart-Gough platform. The advantage of this robot, called Remo I, is that it uses a single impeller, which represents less energy expenditure compared to robots with multiple impellers. The robot can control the position and orientation of the driving force (see Fig. 2b). Furthermore, due to the fact that it can deform, this robot has the potential ability to swim. On the other hand, in [45, 46] the design and modeling of the Remo II robot was presented. The propulsion system of this robot has two thrusters, one on each platform, and a Momentum Control Gyroscope.

2.3.2. Aquatic Glider (Glider)

Gliding underwater robots do not have a propeller drive. These have been designed to slide from the sea surface to a programmed depth, then change their buoyancy and pitch to go in an upward direction until they reach a pre-set point where they descend again and so on. Fig. 2c and d show the Slocum and Seaglider gliders. Advancement is obtained by means of the inclination of the fins, which is achieved by combining small variations in the position and magnitude of the buoyancy force. As a result, a diagonal displacement movement is obtained with minimal energy consumption. While the journey is made, they collect information on temperature, salinity, currents, and other measurements along their trajectory [47, 48, 49, and 50]. Aquatic gliders can have various applications. For example, the Liberade X-Ray robot was designed for surveillance missions and for locating enemy submarines.

Although the speed of these robots is quite low and progress is inevitably linked to vertical movement, their structure is ideal for AUV robots dedicated to oceanographic observation and measurement. The minimum consumption increases the time of the missions to several months and increases the field of action to hundreds of kilometers, this greatly reduces monitoring costs.

2.3.3. Bioinspired

This type of propulsion system is inspired by the physiology of fish or cetaceans, and thus their way of moving through the water. The simplest system consists of a fin with one degree of freedom placed vertically or horizontally at the rear of the underwater vehicle. Its cyclic movement

perpendicular to the plane of the fins, it produces water waves that propel the vehicle forward. This movement produces thrust in only one direction.

In fig. 2e shows the prototype of a swimming robot called Tuna Robot with a rear fin developed by Draper's Laboratory [51]. The design allows you to move a vertical fin from left to right and thereby make this underwater robot navigate. The development of a mathematical model based on the dynamics of a similar robot called PoTuna can be found in an article by [52]. On the other hand,

[53] presents the application of SMA to build the locomotion system of a fish robot.

In fig. 2f the robot called AQUA is presented, which has 6 fins (paddle type) whose synchronized movement allows it to navigate in the water [53].

In [54] the design of an eel robot was presented. Like the eel, this robot completely deforms its body to generate waves in the water and propel itself. In fish-type robots, only the rear part is deformed. The eel robot has multiple vertebrae that allow deformation. These vertebrae are composed of parallel mechanisms with three degrees of freedom.

Another type of underwater vehicle that is propelled by deformation is the one developed by Nanyang Technological University in Singapore, an underwater robot with modular flexible fins that imitate the fins of a ray fish [35]. Each small fin is capable of rotating on the adjacent fin to which it is attached to move in a synchronized manner. This produces a wave movement that propels the whole in one direction.

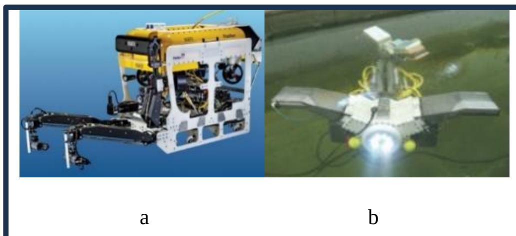
Another concept of navigation by deformation is the AMOEBOT robot [56]. This is a vehicle that propels itself through the water through continuous changes in the shape of its body, similar to the movement of a jellyfish. The way the vehicle navigates is to inflate and deflate certain balloons in a sequence.

2.3.4. Injection

Propulsion by injection consists of collecting water from the outside and then storing it in a tank and finally expelling it using a pump, injecting it into the aquatic environment through a nozzle.

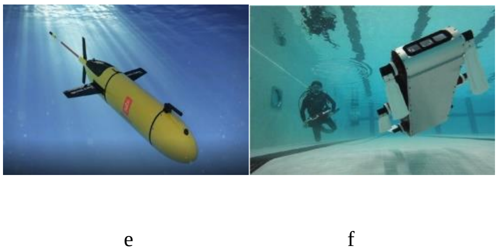
The water is forced out at high pressure through the nozzle and the pushing force of the water produces acceleration in the vehicle. When the orientation of the nozzle can be controlled, it is possible to obtain thrust in various directions. In [56] the implementation of this propulsion system in small underwater robots is presented.

Injection propulsion systems are considered non-conventional systems and can be used in high-speed applications. These provide a viable alternative to the conventional propeller drive. On the other hand, they are more appropriate for protecting the environment, since they prevent damage or injuries to aquatic beings that can be caused by contact with a moving propeller.



Propeller Drive

Aquatic Glider (Glider)



Bioinspired

Fig. (2): Propulsion systems. a) Seaeye Panther-XT [86], b) REMO [42], c) Slocum Glider, d) Seaglider [46], e) Tuna Robot [50], f) AQUA [53].

2.3.5. Magneto hydrodynamic Impeller, MHD

The operating principle of magneto hydrodynamic thrusters consists of circulating electric current through a conductive fluid (e.g. salt water) which is crossed by a magnetic field. The MHD impeller generates the movement of the fluid due to the interaction of the magnetic field and the current that circulates through it. The advantage of this type of propulsion system is that it does not have moving parts, and therefore it will be easier to solve sealing and maintenance problems. However,

The disadvantage it presents is that the electrodes significantly reduce the electromechanical performance, due to their dissolution and the release of gases caused by the electrolysis of the affected materials.

Another problem is that high-intensity magnetic fields are required to obtain a considerable propulsion force in an underwater vehicle. According to [58], the maximum efficiency that this type of impeller can provide is below 50%, because the propulsion force depends on the efficiency of the inductance.

2.3.6. Traction with the seabed

The technique of moving an underwater vehicle through interaction with the seabed is similar to the technique used by terrestrial robots, with the difference that the weight of the vehicle in the water can be neutralized by its buoyancy, and that in water there are viscous friction forces that are much greater than in air. In [59] the Aquarobot was presented, an underwater walking robot with 6 symmetrical legs attached to the body of the robot located in the center. Underwater vehicles could move using legs, wheels, or tracks [60].

In this section, various propulsion systems for underwater robots were presented. It is worth mentioning that there is another form of external propulsion, this is that of devices towed by a boat (towfish). Such devices are mainly used to obtain images of the seabed through sonar (called Side-scan sonar). An example of this type of device could be the MILANA robot, which works by being towed by a boat, while the vehicle maintains a relatively stable depth, to take shots of the bottom off the coast of Barcelona, Spain [61].

2.4. Robotic Arms

To carry out manipulation missions, underwater robots require robotic arms. 'In general, the arms of an ROV are teleoperated using a Master-Slave system. ROVs used in the oil industry frequently have two arms, one to attach the robot to the structure and the other to perform required operations, such as maintenance or repair. Most manipulators have been designed for ROVs and these are controlled by hydraulic actuators. However, arms powered by electric motors have also been developed. These are more useful for IAUVs since they consume less energy than hydraulic actuators [34].

2.5. Energy sources

The power source is one of the most critical components in an underwater robot, mainly in AUVs. The type of energy source defines the operating time of the robot, in addition to the volume and weight of the vehicle. The most common energy sources are:

Table 2: Comparison of energy capacity by weight of the different types of batteries, [43, 63].

Element	Energy Density (Whr/Kg)	Charge Cycles
Alkaline	140	1
Li primary	375	1
Lead-Acid	31.5	~100
Ni-Cd	33	~100
Ni-Zn	58.5	~500
Li-Ion	144	~500
Li-Polymer	193	~500
Silver-Zinc	100	~30
Acid Cell	150-1000	-
Alkaline Cell	250-950	-

Batteries. They are composed of one or more electro-chemical cells that convert the stored chemical energy into electrical energy. They are classified as primary and secondary. The primary batteries cannot be recharged, while the secondary batteries are rechargeable. Primary batteries have a higher energy density than secondary batteries (the case of the primary Li), however, their use is generally more expensive. Within the type of primary batteries, the most common and affordable are the alkaline ones. The batteries mostly used in AUVs are secondary ones. Until recently, the most used were Silver-Zinc batteries, but recent advances in Li-Ion batteries have made these an attractive alternative [17].

Fuel cells. They generate electrical energy through a chemical reaction between a fuel (usually hydrogen) and an oxidizing agent (usually oxygen). Although there is a great diversity of fuel cells, they are all composed of an anode, a cathode, and an electrolyte that allows the movement of charges. The material used as an electrolyte gives rise to the different types of fuel cells. Unlike batteries, a fuel cell requires a constant flow of fuel and oxidizing element to generate electrical energy. In general, they have greater autonomy than batteries, but it is necessary that the fuel tanks be pressurized.

In [63], a summary of the most important aspects of batteries and their use in underwater systems is presented. Table 2 presents a comparative table of the different batteries and fuel cells and their energy density.

3. Modeling of Underwater Robots

In this section, the kinematic and dynamic modeling of underwater robots will be presented. Kinematic modeling consists of equations that relate the different types of coordinates used to express the speed of the robot. On the other hand, in dynamic modeling, the forces that act on the robot when it navigates are described. The derivation of the equations of motion for bodies immersed in water is briefly presented. Special emphasis is placed on this section because, in underwater robots, velocity and its temporal derivative are measured with respect to the body's reference frame. Only the most important equations are presented, without losing sight of the didactic purpose of this work [1].

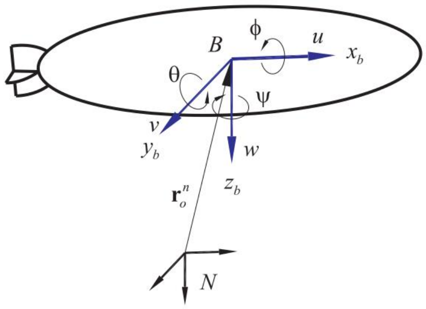


Fig 3: Notation in underwater robotics.

3.1. Kinematic Modeling of Underwater Robots

When analyzing the movement of an underwater robot, it is necessary to define two reference frames to describe its movement, these are:

Inertial references frame **NED**. This frame is located on the surface of the earth and its name indicates the English acronym for North-East-Down. In this framework, the x-axis points north, the y-axis points east, and the z-axis points down and is normal to the Earth's surface. In this way the x-y plane is tangent to the surface of the earth. In this work, this framework is referred to simply by N.

Body reference frame **B**. This reference frame is fixed to the body of the robot (Body). The origin O of this reference frame is generally made to coincide with the center of gravity of the body when it is in the principal plane of symmetry, or at some other convenient point if this is not the case. The axes of this frame are chosen in such a way that they coincide with the main axes of inertia, x_b being the longitudinal axis (which goes from back to front), and b the transverse axis (which goes from one side to the other), and z_b being It is directed downwards.

In the realm of maritime navigation and underwater robotics, there is a convention established by the SNAME (Society of Naval Architects and Marine Engineers) for conveying information regarding the position, orientation, and forces acting upon a vehicle. In Table (3), you will find a list of movement names for marine vehicles, along with notation for their position, speed, and force. In fig. (3) you can see this notation [64].

Table 3: Notation of the movement of marine vehicles [64].

Motion		Position	Speed	Force
Translation in x	Surge	x	u	X
Translation in y	Sway	y	v	Y
Translation in z	Heave	z	w	Z
Rotation in x	Roll	φ	p	K
Rotation in y	Pitch	θ	q	M
Rotation in z	Yaw	ψ	r	N

To represent the position of the vehicle with respect to the inertial frame N we have the vector:

$$\eta = \begin{bmatrix} \mathbf{r}^n \\ \Theta^o \end{bmatrix} \dots\dots\dots\dots (1)$$

Where $\mathbf{r}_o^n = [x\ y\ z\ ]^{\boldsymbol{T}}$= represents the position of the reference frame of the body **B** with respect to the frame N, while Θ is a vector of parameters that allows defining the relative orientation between these two reference frames. In this case, the orientation parameters can be the Euler angles or the quaternion of the Euler parameters, p^b.

The speed of the vehicle is represented by the vector:

$$v = \begin{bmatrix} \mathbf{v}_o^b \\ \mathbf{w}_b^b \end{bmatrix} \dots\dots\dots\dots (2)$$

Here$\mathbf{v}_o^b = [x\ y\ z\ ]^{\boldsymbol{T}}$: is the linear speed of the vehicle measured in frame coordinates of body B, while $\mathbf{w}_b^b = [x\ y\ z\ ]^{\boldsymbol{T}}$: represents the angular velocity of the body with respect to the inertial frame measured in the reference frame of body B. These velocities are also usually denoted by the vectors ν1 = $\boldsymbol{v_1} = \mathbf{v}_o^b$ and $\boldsymbol{v_2} = \mathbf{w}_b^b$.

To describe the forces to which the vehicle is subject, use the notation:

$$\tau = \begin{bmatrix} \mathbf{f}_o^b \\ \mathbf{n}_o^b \end{bmatrix} \dots\dots\dots\dots (3)$$

Where $\mathbf{f}_o^b = [x\ y\ z\ ]^{\boldsymbol{T}}$and $\mathbf{n}_o^b = [x\ y\ z\ ]^{\boldsymbol{T}}$ are the vectors of force and moment exerted on the body measured in the frame of reference of the body B.

3.1.1. Rotation Matrix

Rotation matrices are the most widespread method for describing orientations, mainly due to the ease of using matrix algebra. These matrices describe the mutual orientation between two coordinate systems; their column vectors are the directing cosines of the axes of one coordinate system with respect to another.

Given a vector $\mathbf{r}^b$ expressed in frame B coordinates, then that same vector, expressed in frame A coordinates is given by: $\mathbf{r}^a = \mathbf{R}_b^a\,\mathbf{r}^b$.
Where $\mathbf{R}_b^a$ represents the rotation matrix of frame B with respect to frame A.

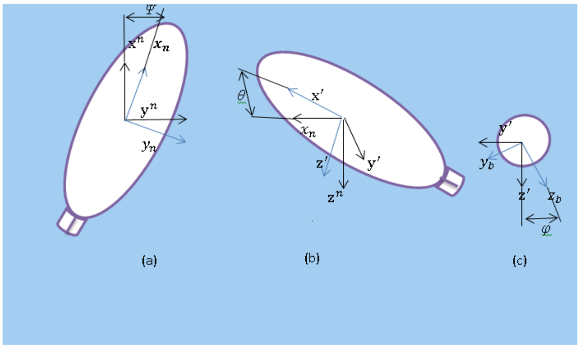


Fig 4: Sequence of rotations of the Euler angles: (a) Yaw, (b) Pitch, and (c) Roll.

The robot schematic appears in the final orientation after the corresponding rotation.

3.1.2. Euler's angles

Euler established that any two independent orthonormal coordinate frames (with a common origin) can be related by a sequence of no more than three rotations around the coordinate axes. This means that if the sequence of axes to be rotated is known, only three Euler angles are needed to completely define the total rotation.

Given a sequence of Euler angles, it is possible to find the corresponding rotation matrix. The convention used in underwater robotics for Euler angles consists of the following sequence:

- ❖Rotation of the reference frame by an angle **ψ** around the **z**-axis to obtain frame **B**.
- ❖Rotation of the reference frame by an angle **θ** around the **y**-axis to obtain frame **B**.
- ❖Rotation of the reference frame by an angle **φ** around the **x**-axis to obtain frame **B**.

In fig. 4 this sequence of rotations of the Euler angles is presented.

Thus: $\boldsymbol{R}_{x,\varphi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\varphi & -s\varphi \\ 0 & s\varphi & c\varphi \end{bmatrix}$

$$\boldsymbol{R}_{y,\theta} = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \quad \boldsymbol{R}_{z,\psi} = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Where s· = sin (·) and c· = cos (·).

The order of these rotations is not arbitrary; they are carried out from the reference frame N to the frame B. The matrix representing these rotations is denoted by $\mathbf{R}_b^n = \mathbf{R}_b^{n\,T}$. The transposed matrix implies that the same result is obtained by transforming a vector from reference frame B to frame N, reversing the order of rotation. ´ This sequence of rotations is mathematically equivalent to$\mathbf{R}_b^n = \boldsymbol{R}_{x,\varphi}.\boldsymbol{R}_{y,\theta}\,.\boldsymbol{R}_{z,\psi}$.

Performing this operation you obtain:

$$\mathbf{R}_b^n = \begin{bmatrix} c\psi c\theta & -s\psi\, s\theta + c\psi c\theta s\varphi & s\psi\, s\varphi + c\psi c\varphi s\theta \\ s\psi c\theta & c\psi\, c\theta + s\varphi c\theta s\psi & -c\psi\, s\varphi + s\theta s\psi c\varphi \\ -s\theta & c\theta s\varphi & c\theta c\varphi \end{bmatrix} \quad (4)$$

To perform the inverse operation, that is, determine the Euler angles once the rotation matrix is known, the following expressions can be derived:

$$\varphi = \operatorname{atan2}(r_{32}, r_{33}) \;\ldots\ldots\ldots\ldots (5)$$

$$\theta = -\sin^{-1}(r_{31}) = -\tan^{-1}\left[\frac{r_{31}}{\sqrt{1 - r_{31}^2}}\right] \quad (6)$$

$$\psi = \operatorname{atan2}(r_{21}, r_{11}) \; (7)$$

where r_{ij} denotes the element (i, j) of the rotation matrix $\mathbf{R}_b^n$, and atan2 (y, x) is the arctangent function of two arguments real x,y, and satisfies that $-\pi \leq \operatorname{atan2} \leq \pi$.

Speed Transformation. The transformation that relates the linear velocity vector in an inertial reference frame to the reference frame of the body can be expressed as follows:

$$\dot{\mathbf{r}}_0^b = \mathbf{R}_b^n\,\mathbf{v}_0^b \;\ldots\ldots\ldots\ldots (8)$$

On the other hand, the angular velocity vector of the body ω_b^b and the velocity vector of the Euler angles are related by a transformation matrix T_Θ as shown below:

$$\dot{\Theta} = T_\Theta \omega_b^b \;\ldots\ldots\ldots\ldots (9)$$

where T_Θ is given by: $T_\Theta = \begin{bmatrix} 1 & s\varphi t\theta & c\varphi t\theta \\ 0 & c\varphi & -s\varphi \\ 0 & s\varphi c\theta & c\varphi c\theta \end{bmatrix} \ldots\ldots\ldots\ldots (10)$

and t· = tan(·).

The above expressions can be summarized as follows:

$$\dot{\eta} = \mathbf{J}\nu \;\ldots\ldots\ldots\ldots (11)$$

where:

$$\mathbf{J}(\nu) = \begin{bmatrix} \mathbf{R}_b^n & 0 \\ 0 & \mathrm{T}_\Theta \end{bmatrix} \ldots\ldots\ldots\ldots (12)$$

and $\dot{\eta} = \frac{d(\eta)}{dt}$

3.1.3. Euler parameters

Another alternative is to represent orientation using Euler parameters. The main motivation for using these parameters is to avoid the singularities suffered by the representation using Euler angles.

A quaternion is composed of four parameters:

$$\mathbf{p} = [\boldsymbol{e}_0\, \boldsymbol{e}_1\, \boldsymbol{e}_2\, \boldsymbol{e}_3\,]^T \ldots\ldots\ldots\ldots (13)$$

that satisfy a unit norm constraint, $\mathrm{p}^\mathrm{T}\mathrm{p} = 1$.

The expression of the rotation matrix in terms of the Euler parameters is the following:

$$\boldsymbol{R}_{(\boldsymbol{p})} = \begin{bmatrix} 1-2(\mathbf{e}_2^2+\mathbf{e}_2^3) & 2(\mathbf{e}_1\mathbf{e}_2+\mathbf{e}_0\,\mathbf{e}_3) & 2(\mathbf{e}_1\mathbf{e}_3+\mathbf{e}_0\,\mathbf{e}_2) \\ 2(\mathbf{e}_1\mathbf{e}_2+\mathbf{e}_0\,\mathbf{e}_3) & 1-2(\mathbf{e}_1^2+\mathbf{e}_3^2) & 2(\mathbf{e}_2\mathbf{e}_3+\mathbf{e}_0\,\mathbf{e}_1) \\ 2(\mathbf{e}_1\,\mathbf{e}_3+\mathbf{e}_0\,\mathbf{e}_2) & 2(\mathbf{e}_2\mathbf{e}_3+\mathbf{e}_0\,\mathbf{e}_2) & 1-2(\mathbf{e}_1^2+\mathbf{e}_2^2) \end{bmatrix} (14)$$

In compact form, you have:

$$\mathbf{R}(\mathbf{p}) = I_3 + 2\mathrm{e}_0\,\mathrm{S}(e) + 2\mathrm{S}(e)2$$

Where $\boldsymbol{e} = [\boldsymbol{e_1}\, \boldsymbol{e_2}\, \boldsymbol{e_3}\,]^T$ is a subvector of **p** and **S** (·) is the matrix operator of the cross product.
Given the vector ***e*** we have

$$\mathrm{S}(e) = \begin{bmatrix} 0 & -\boldsymbol{e_3} & \boldsymbol{e_2} \\ \boldsymbol{e_3} & 0 & -\boldsymbol{e_1} \\ -\boldsymbol{e_2} & \boldsymbol{e_1} & 0 \end{bmatrix} \ldots\ldots\ldots\ldots (15)$$

Speed Transformation. To carry out the transformation of linear velocities, the same operation is carried out as in the case of Euler angles, simply by using the rotation matrix.

The transformation of the angular velocity can be derived by substituting expression (14) into the differential equation. $\dot{\mathbf{R}}_b^n = \mathbf{R}_b^n\,\mathrm{S}(\omega_b^b)$

Through some operations, you have:

$$\dot{\mathrm{p}} = \mathrm{T}_\mathrm{p}\omega_b^b \ldots\ldots\ldots\ldots (16)$$

$$\mathrm{T}_\mathrm{p}(\mathrm{p}) = \begin{bmatrix} -\boldsymbol{e_1} & -\boldsymbol{e_2} & -\boldsymbol{e_3} \\ \boldsymbol{e_0} & -\boldsymbol{e_3} & \boldsymbol{e_2} \\ \boldsymbol{e_3} & \boldsymbol{e_0} & -\boldsymbol{e_1} \\ -\boldsymbol{e_2} & \boldsymbol{e_1} & \boldsymbol{e_0} \end{bmatrix} \ldots\ldots\ldots\ldots (17)$$

The above expressions can be summarized as follows:

$$\dot{\boldsymbol{\eta}} = \mathbf{J}\nu \ldots\ldots\ldots\ldots (18)$$

where:

$$\mathbf{J}(\nu) = \begin{bmatrix} \mathbf{R}_b^n & 0 \\ 0 & \mathrm{T}_\Theta \end{bmatrix} \ldots\ldots\ldots\ldots (19)$$

In this case $\dot{\boldsymbol{\eta}} = [\dot{\mathbf{r}}_0^b\; \dot{\boldsymbol{q}}\,]^{\boldsymbol{T}}$

3.2. Dynamics of Underwater Robots

The dynamic model of an underwater robot describes the relationship between the movements of the robot and the forces that are exerted on it. In this way, the external forces necessary for the robot to move in a certain way can be calculated, or on the contrary, the movement generated by the external forces to which the robot is subject can be determined.

Next, the *Newton-Euler* equations of motion for bodies immersed in water will be presented. Submerged bodies are subject to different types of forces. These forces are mainly inertial forces, hydrodynamic forces and restoration forces.

The dynamic model of an underwater robot can be written in its compact form as shown below:

$$\mathrm{M}\dot{\nu} + \mathrm{C}(\nu)\nu + \mathrm{D}(\nu)\,\nu + \mathrm{g}(\eta) = \tau + \mathrm{g}_0 + \mathrm{w} \ldots\ldots\ldots\ldots (20)$$

$$\tau = \mathrm{B_t u_t} \ldots\ldots\ldots\ldots (21)$$

Where the matrix **M** contains the elements of the inertia matrix and the added mass matrix (the concept of added mass will be presented later); For its part, the matrix **C** consists of the matrix of centrifugal and Coriolis forces of the rigid body and the added mass; the **D** matrix is the viscous force matrix; and the vector **g(η)** represents the restitution forces (which are composed of the force of gravity and the force of buoyancy).

On the other hand, the vector τ represents the forces exerted by the thrusters (or any other force-generating element) on the underwater robot. The elements of the control matrix $\mathbf{B_t}$ depend on the configuration of each robot, its control surfaces, the number of thrusters, and the location and orientation of the thrusters. The vector $\mathbf{u_t}$ is composed of the forces that are generated in each impeller. on the other hand, the vector $\mathbf{g_0}$ represents the force generated by the ballast control.

The vector **w** represents environmental disturbances (such as waves, wind, and ocean currents). The vector formulation was developed in [65] inspired by the structure of manipulator robot models. The following sections describe the forces mentioned above in greater detail.

3.2.1. Inertial Forces

The Newton-Euler equations for a rigid body are the following:

$$\mathbf{f}_c^b = \frac{d}{dt}(m v_c^b) \;\ldots\ldots\ldots\ldots (22)$$

$$\mathbf{n}_c^b = \frac{d}{dt}(I_c\, \omega_c^b) \;\ldots\ldots\ldots\ldots (23)$$

where $\mathbf{f}_c^b$ and $\mathbf{n}_c^b$ are the force and torque at the center of mass of the body; m and I_c are the mass and inertia matrix of the body, respectively. In this case, the mass matrix is given in the reference frame of the body. The vectors v_c^b and ω_c^b represent the linear and angular velocity of the body with respect to the inertial reference frame N but measured in the reference frame of the body **B**.

For underwater robots, the equations of motion are derived given an arbitrary position of the origin ***O*** of the reference frame of the body **B**. This is because some hydrodynamic properties can be calculated more easily at points that may not coincide with the center of robot mass.

The linear velocity of the center of mass with respect to frame **N** measured in the reference frame of body **B** can be expressed as follows: $\mathrm{v}_c^b = \mathrm{v}_0^b + \omega_b^b \times \mathbf{r}_\mathrm{g}^b$ (24)

Where $\mathbf{r}_g^b$ is the position of the center of mass with respect to the origin of frame **B**. to determine the acceleration of the center of mass with respect to the reference frame **N**, we first consider that $\mathbf{v}_c^n = \mathbf{R}_b^n \mathbf{v}_c^b = \mathbf{R}_b^n \mathbf{v}_c^b = (\mathrm{v}_0^b + \omega_b^b \times \mathbf{r}_\mathrm{g}^b)$. Differentiating $\mathbf{v}_c^b$ with respect to time gives the following expression:

$$\dot{\mathrm{v}}_c^n = \mathbf{R}_b^n [\dot{\mathbf{v}}_0^b + \dot{\omega}_b^{\boldsymbol{b}} \times \mathbf{r}_\mathrm{g}^b + \omega_b^b \times \mathrm{v}_0^b + \omega_b^b \times (\omega_b^b \times \mathbf{r}_\mathrm{g}^b) \ldots\ldots\ldots\ldots (25)$$

Therefore, substituting the value of the derivative (25) into equation (22), and given that $\mathbf{f}_0^b = \mathbf{f}_c^b$ for translational movements, the following expression is obtained:

$$\mathbf{f}_0^b = m[\dot{\mathbf{v}}_0^b + \dot{\omega}_b^{\boldsymbol{b}} \times \mathbf{r}_\mathrm{g}^b + \omega_b^b \times \mathrm{v}_0^b + \omega_b^b \times (\omega_b^b \times \mathbf{r}_\mathrm{g}^b) \ldots\ldots\ldots\ldots (26)$$

This allows calculating the force at the origin of the body's reference frame, that is, ***O***.

On the other hand, the angular momentum with respect to point ***O*** and point ***C*** is given by the following expressions

$$\mathbf{h}_0^b = \boldsymbol{I}_c\, \omega_b^b + m\mathbf{r}_\mathrm{g}^b \times v_0^b \;\mathrm{y}\; \mathbf{h}_c^b = \mathbf{h}_0^b - m\mathbf{r}_\mathrm{g}^b \times v_c^b$$

Considering that $\mathbf{h}_0^b = \mathbf{R}_b^n \mathbf{h}_c^b$, the time derivative of the angular momentum with respect to point ***C*** is the following:

$$\dot{\mathbf{h}}_c^n = \mathbf{R}_b^n [\, \boldsymbol{I}_0 \dot{\omega}_b^{\boldsymbol{b}} \times m\mathbf{r}_\mathrm{g}^b (\dot{\mathrm{v}}_c^b - \dot{\mathrm{v}}_c^b) + \omega_b^b \times (\boldsymbol{I}_0 \omega + m\mathbf{r}_\mathrm{g}^b \times (v_0^b - \mathrm{v}_c^b))]$$

On the other hand, the moment $\mathbf{n}_c^n$ is equal to $\mathbf{n}_c^n = \dot{\mathbf{h}}_c^n$ y $\mathbf{n}_c^n = \mathbf{R}_b^n (\mathrm{m}_0^b - \mathbf{r}_\mathrm{g}^b \times \mathbf{f}_c^b)$ being in this case $\mathbf{f}_c^b = m(\dot{\mathrm{v}}_{\boldsymbol{c}}^b + \omega_b^b \times \mathrm{v}_c^b)$. By equating the expressions of nn c and performing algebraic operations, the equation of the moment at the origin of frame B is finally obtained:

$$\mathbf{n}_0^b = \boldsymbol{I}_0 \omega_b^b + \omega_b^b \times (\boldsymbol{I}_0 \omega_n^{\boldsymbol{b}}) + m\mathbf{r}_\mathrm{g}^b + \dot{v}_0^b + m\mathbf{r}_\mathrm{g}^b \times (\omega_b^b \times \mathrm{v}_0^b) \ldots\ldots\ldots\ldots (27)$$

Equations (26) and (27) can be written in matrix form, as shown below:

$$\begin{bmatrix} \mathbf{f}_n^b \\ \mathbf{n}_0^b \end{bmatrix} = \mathrm{M}_R \begin{bmatrix} \dot{\mathrm{v}}_0^b \\ \dot{\omega}_b^b \end{bmatrix} + \mathrm{C}_R(\mathrm{v}_0^b, \omega_b^b) \begin{bmatrix} \mathrm{v}_0^b \\ \omega_b^b \end{bmatrix} \quad (28)$$

Where $\mathbf{M}_R$ is the mass matrix of the rigid body, and $\mathbf{c}_R(v)$is the centrifugal and Coriolis force matrix. The mass matrix is given as follows

$$\mathbf{M}_R = \begin{bmatrix} m\boldsymbol{I}_3 & -m\mathrm{S}(\mathbf{r}_\mathrm{g}^b) \\ m\mathrm{S}(\mathbf{r}_\mathrm{g}^b) & \boldsymbol{I}_0 \end{bmatrix} \ldots\ldots\ldots\ldots (29)$$

The matrix of centrifugal and Coriolis forces can take different forms. In this case, one is adopted that makes this matrix antisymmetric. An antisymmetric matrix has the property $\mathbf{c}_R(v) = -\mathbf{c}_R(v)^T$. Therefore, this matrix is given by the following expression:

$$\mathbf{c}_R(\boldsymbol{v}) = \begin{bmatrix} \mathbf{0}_3 & -\mathrm{S}(\mathbf{M}_{R11}\boldsymbol{v}_1 + \mathbf{M}_{R12}\boldsymbol{v}_2) \\ -\mathrm{S}(\mathbf{M}_{R11}\boldsymbol{v}_1 + \mathbf{M}_{R12}\boldsymbol{v}_2) & -\mathrm{S}(\mathbf{M}_{R21}\boldsymbol{v}_1 + \mathbf{M}_{R22}\boldsymbol{v}_2) \end{bmatrix} \quad (30)$$

3.2.2. Hydrodynamic Forces

The hydrodynamic forces that affect a submerged body are quite complex since they depend on many variables such as the characteristics of the fluid, temperature, pressure and the geometric shape of the body, among others. The hydrodynamic forces are the added mass forces and the viscous force

Added Mass

The added mass is a force that opposes the movement of the body in the fluid and depends on the acceleration of the body, as it may also be on the speed. The added mass is usually associated with the amount of fluid that is around the body, and that must accelerate when the body accelerates as well. Unlike the mass of a rigid body, the added mass does not always comply with the property of being constant and symmetrical, nor is it always diagonal.

The most reliable way to measure mass at all is through experimentation. The way it is done is to accelerate the body in the direction of the axes and measure the variation in the required force.

The added mass matrix is a square matrix of order 6:

$$\mathbf{M}_A = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix} \quad (31)$$

On the other hand, this matrix can be expressed in terms of 4 submatrices:

$$\mathbf{M}_A = \begin{bmatrix} \mathbf{M}_{A_{11}} & \mathbf{M}_{A_{12}} \\ \mathbf{M}_{A_{21}} & \mathbf{M}_{A_{22}} \end{bmatrix} \;\dots\dots\dots\dots (32)$$

The matrix of centrifugal and Coriolis forces of the added mass ˜ can take different forms. As in the case of $\mathrm{c}_R(v)$, one is used that makes this matrix antisymmetric:

$$\mathbf{c}_R(\boldsymbol{v}) = \begin{bmatrix} \mathbf{0} & -\mathrm{S}(\mathbf{M}_{\boldsymbol{R11}}\boldsymbol{v}_1 + \mathbf{M}_{\boldsymbol{R12}}\boldsymbol{v}_2) \\ -\mathrm{S}(\mathbf{M}_{\boldsymbol{R11}}\boldsymbol{v}_1 + \mathbf{M}_{\boldsymbol{R12}}\boldsymbol{v}_2) & -\mathrm{S}(\mathbf{M}_{\boldsymbol{R21}}\boldsymbol{v}_1 + \mathbf{M}_{\boldsymbol{R22}}\boldsymbol{v}_2) \end{bmatrix} \;\dots\dots\dots\dots (33)$$

Viscous Forces

These forces are the result of the friction exerted by the viscosity of the fluid on the body. They are usually classified according to their effect on the body: drag force and lifting force. Drag forces oppose movement and act in the opposite direction, while lift forces are perpendicular to the relative movement of the body over the fluid. Like added mass, the only way to have reliable knowledge of the magnitudes of these forces is through experimentation. Viscous damping forces can be modeled as follows:

$$f(\boldsymbol{u}) = -\frac{1}{2}\,\boldsymbol{p}_a\,\boldsymbol{C}_D\boldsymbol{A}_1\,|\boldsymbol{u}|\boldsymbol{u} \; (34)$$

Where u is the speed of the vehicle, A is the area projected in a plane orthogonal to the direction of the speed, $\boldsymbol{C}_D$ is the drag coefficient based on a representative area, and $\boldsymbol{p}_a$ is the density of the water. The drag coefficient $\boldsymbol{C}_D(\boldsymbol{R}_e)$ is a function of the Reynolds number[1]. The total damping matrix is defined in the following way

$$\boldsymbol{D}_{(v)} = \boldsymbol{D}_1 + \boldsymbol{D}_n \;\dots\dots\dots\dots (35)$$

Where $\boldsymbol{D}_1$ is the linear damping matrix and $\boldsymbol{D}_n$ is the nonlinear damping matrix. The matrix **D** has the following properties: it is real, non-symmetrical and strictly positive. In general, the damping of an underwater vehicle moving in three-dimensional space at high speeds is highly nonlinear and coupled. However, a rough approach is to assume that the robot performs a decoupled movement. This suggests that the structure of the matrix **D** with only linear or quadratic terms on the diagonal

$$D = -\,\mathrm{diag}\{\boldsymbol{X}_u, \boldsymbol{Y}_v, \boldsymbol{Z}_w, \boldsymbol{K}_p, \boldsymbol{M}_{q,}\boldsymbol{N}_r\}$$

$$-\,\mathrm{diag}\{\boldsymbol{X}_{|u|u}|u|, \boldsymbol{Y}_{|u|v}|v|, \boldsymbol{Z}_{|w|w}|v|, \boldsymbol{K}_{|p|p}|p|, \boldsymbol{M}_{|q|q}|q|\boldsymbol{N}_{|r|r}|r|\} \; (36)$$

It is necessary to note that this expression is not valid when combined movements are performed. Particularly in the case of quadratic terms since the results obtained would be conceptually erroneous from a mathematical point of view.

To obtain the hydrodynamic parameters of a robot, the best way is experimentation. However, it is possible to find specialized software such as PowerFlow® [66] that can be useful to determine these parameters. In addition, work has also been carried out to find mathematical expressions that determine these parameters from the geometry of the robot.

3.3. Restoration Forces

In addition to hydrodynamic forces, underwater vehicles are affected by gravity and buoyancy forces. These forces are called restitution forces. The gravitational force $\mathbf{f}_{\mathrm{g}}^{b}$ acts on the center of gravity which is defined by the vector $\mathbf{r}_{\mathrm{g}}^{b} = [x_{\mathrm{g}}\; y_{\mathrm{g}}\; z_{\mathrm{g}}]^T$. Similarly, the buoyant force $\mathbf{f}_{by}^{b}$ by acts on the center of buoyancy defined by the vector$\mathbf{r}_{by}^{b} = [x_{by}\; y_{by}\; z_{by}]^T$. The weight of a body immersed in water and the buoyant force are defined as follows:

$$\mathrm{W} = \mathrm{mg} \;\dots\dots\dots\dots (37)$$

---

[1] The Reynolds number is a dimensionless parameter commonly used in fluid mechanics and is used to determine whether a flow is laminar or turbulent. It is defined as $\boldsymbol{R}_e = \frac{\mathrm{LV}}{\mathrm{v}}$ Where **L** and **V** are a characteristic length and velocity, respectively, and ν is the kinematic viscosity. L depends on the geometry of the problem of interest [67].

$$\mathrm{B} = \rho_a \, \mathrm{g} \, \mathrm{V} \; \ldots\ldots\ldots\ldots (38)$$

Where g is the acceleration due to gravity and V is the volume displaced by the robot.

Therefore $\mathbf{f}_{\mathrm{g}}^{n} = [0 \; 0 \; \mathrm{W}\,]^{T}$ and $\mathbf{f}_{\mathrm{by}}^{n} = [0 \; 0 \; \mathrm{B}\,]^{T}$. The Gravity and buoyancy forces can be transformed to the body's reference frame simply by multiplying by the inverse of the rotation matrix $\mathbf{R}_{\mathrm{b}}^{n}$, i.e. $\mathbf{f}_{\mathrm{g}}^{n} = \mathbf{R}_{\mathrm{b}}^{n-1}\, \mathbf{f}_{\mathrm{g}}^{n}$ and $\mathbf{R}_{\mathrm{by}}^{n-1}\, \mathbf{f}_{\mathrm{by}}^{n}$. The force and moment of restoration in the frame of reference of the body is given as follows:

$$\mathbf{g}_{(v)} = -\begin{bmatrix} \mathbf{f}_{\mathrm{g}}^{b} + \mathbf{f}_{\mathrm{by}}^{b} \\ \mathbf{r}_{\mathrm{g}}^{b} \times \mathbf{f}_{\mathrm{g}}^{b} + \boldsymbol{r}_{\mathrm{g}}^{b} \times \mathbf{f}_{\mathrm{by}}^{b} \end{bmatrix} \quad (39)$$

In this section, a brief review of the formulation presented in (Fossen, 2002), among other sources, on the modeling of submerged bodies was presented. The objective was to succinctly present the formulation of the equations of motion of underwater robots. These relationships are useful for the simulation, analysis, design, and control of these robots.

A useful (and educational) tool for modeling underwater robots is the GNC Toolbox for Matlab developed by [68].

4. Control of Underwater Robots

In this section, there will be a review of the strategies, methods, and control laws that have been proposed for underwater robots. Before this, some relative concepts will be presented to the components of an underwater robot control system. In [68, 69] the concept of the Mission Control System (MCS) is presented. The MCS is the set of programs responsible for carrying out the desired mission. An MCS is usually equipped with a graphical interface that allows the operator to command different tasks that make up the mission. The MCS contains the Guidance, Control and Navigation elements of the robot. Mission tasks are generally concurrent and their handling depends on the state of the vehicle and environmental conditions; therefore, the MCS manages the tasks, eventually deleting them and defining their sequence (modifying and prioritizing). The MCS is made up of the following systems:

Guidance System. The guidance system generates the trajectories that you want the robot to follow during a mission. This information (the position, speed and acceleration of the robot) is sent to the Control System which will try to reach the desired references. The guidance system has as inputs the Guide Points defined by the user, and information from the Navigation system. In addition, it can receive information about the situation of the environment (e.g. ocean currents), the topography of the seabed, and data from a sonar for the detection of obstacles. However, currently, some AUVs have a dynamic planning module that allows them to replan during the mission and pass guide points that were not previously defined in the guidance module [70].

Control system. The control system is responsible for calculating the necessary forces that the propulsion system must generate for the robot to reach the desired references. The construction of the control system involves the design and tuning of the Control Laws that will regulate the movements of the robot. The control system receives information on the desired position, speed and acceleration and the current state of these variables is measured through the robot's sensors. This system may consist of classical control laws, non-linear control, intelligent control, behavior-based systems, etc.

Navigation system. The navigation system receives information from the position, speed, and acceleration sensors of the underwater robot. Using an Observer or other algorithms, it processes this information and subsequently sends it to the Guidance System and the Control System.

In [71] a classification of the types of AUV MSCs is presented in which 4 control architectures were identified: Hierarchical, Distributed, Layered (subsumption), and Hybrid. On the other hand, in [72] a classification of control architectures is made that considers the aspects of artificial intelligence and interaction with the environment. In this latest work, the classification of control architectures would be as follows: Deliberative, Reactive, and Hybrid. It is considered that this last classification is more general and includes the one made in [71]. According to [72], these architectures are briefly described:

Deliberative Architecture. This pyramid-type architecture divides the system into levels from highest to lowest responsibility. The higher levels are in charge of the mission that the robot must perform, and the lower levels solve particular problems. Communication is only possible between two adjacent layers; the higher layer sends commands to the subsequent lower level. Deliberative architecture is based on planning and a model of the world. This allows you to reason and make predictions about the environment. The analysis of data obtained from sensors identifies the real world and is used to plan new actions.

Reactive Architecture. The reactive or behavior-based architecture uses a parallel structure, where all the modules of the system can communicate directly with each other, without the need for the supervision of a higher intermediary level. The behavior obtained from the robot is based on a sequence of phases with a set of active behaviors that continuously react to the detected situations. Global behavior arises from the combination of active elements, which follow the principle of detection-reaction, and can interact with dynamic means. Because multiple reactions could change the overall perspective of the mission, sometimes the robot could behave in unforeseeable ways. To avoid this, a priority arbitration system is established, so that at the time of any conflict, the situation is resolved and the established goal is returned to.

Hybrid Architecture. It is an architecture that combines deliberative and reactive architectures, where the advantages of each are taken. The system is generally divided into three levels: the deliberative layer, which is based on planning; the control execution layer, and the reactive functional layer. These layers use different levels of abstraction. The high-level uses the hierarchical architecture to implement the strategies and functionality of the system. The lowest level uses reactive architecture, to control the subsystem hardware according to the interaction with the environment, but controlled by the control execution layer. The reactive layer consists of some autonomous modules that can execute tasks independently. In an emergency situation, changes can be made so that the highest level assumes control. Once the control architectures have been described, below is a review of the (low-level) control systems that have been proposed in the literature [71,72].

4.1. Classic Control

To control underwater robots, the different control techniques that have previously been proposed for other systems can be used. This is the case of closed-loop controllers that feed back the signals measured by the robot's sensors. In the case of a PID controller, the control law is expressed as follows:

$$\boldsymbol{\tau}_{PID} = \mathbf{J}(\mathbf{v})^{\mathbf{T}} \left[\boldsymbol{K}_{p\tilde{\eta}} + \boldsymbol{K}_{d\dot{\eta}} + \boldsymbol{K}_i \int \tilde{\eta}\,(\boldsymbol{\sigma}) d\boldsymbol{\sigma} \right] \quad (40)$$

Where $\tilde{\eta} = \eta_d - \eta_d$ is the error between the actual and desired position, $\boldsymbol{K}_p$ is the proportional gain matrix, $\boldsymbol{K}_d$ derivative gains, and $\boldsymbol{K}_i$ is the integral gain matrix. On the other hand, the PID controller with acceleration feedback has also been proposed.

$$\boldsymbol{\tau}_{PID} = \mathbf{J}(\mathbf{v})^{\mathbf{T}} \left[\boldsymbol{K}_{p\tilde{\eta}} + \boldsymbol{K}_{d\dot{\eta}} + \boldsymbol{K}_i \int \tilde{\eta}\,(\boldsymbol{\sigma}) d\boldsymbol{\sigma} \right] - \mathbf{H}\dot{\boldsymbol{v}} \quad (41)$$

Where the matrix **H** can be constant or frequency-dependent. The purpose of acceleration feedback is that the system is less sensitive to external disturbances such as ocean currents. This concept is explained in [68].

Given the structure of the model presented in eq. (20) the different control laws that have been proposed for robot manipulators could be extrapolated.

4.2. Nonlinear Control

In [74] a sliding mode controller for underwater robots was presented. The advantages of this type of controller are that it works directly with nonlinear terms; it is highly robust to imprecise models and to the presence of disturbances that are difficult to measure or estimate. In [75] an autopilot based on sliding modes was designed to control the direction, speed, and depth of an underwater vehicle. In [76] the synthesis of two robust controllers (one based on sliding modes and the other based on linear matrix inequalities, LMI) techniques for underwater robots is presented [73].

On the other hand, various authors have proposed adaptive controllers, since they can be a solution to the problem of determining the hydrodynamic parameters of the robot (it is difficult to obtain these parameters through mathematical formulations, and on the other hand, determining them experimentally leads to an economic cost and time). In [77] a pair of multiple-input, multiple-output self-tuning autopilots is presented. In this work, a self-tuning online quadratic linear controller is presented, and on the other hand, a control law is based on a first-order approximation of the dynamics of the open-loop system with recursive online identification. In [78] two controllers are presented to compensate for the uncertainties of the ROV model, these are an adaptive controller based on passivity, and a hybrid controller (adaptive and sliding modes). In [79] an adaptive control for a robot that operates in shallow waters was presented.

4.3. Smart Control

Controllers based on neural networks for underwater robots were presented in [80, 81].

In [81] the control system consisted of a neural network and a learning algorithm. The neural network consists of numerous layers of neurons. The input layer receives the desired position and speed, the current position and speed, and signals from the learning algorithm. The output of the neural network is what controls the vehicle. The learning algorithm adjusts the values of the neuron weighting parameters, depending on the error between the desired state and the real one. In [82] a review is made of different works in which neural networks have been applied to the control of underwater robots and a classification of the strategies presented is made.

In [83] the design of a fuzzy logic controller for depth control of underwater robots is presented. This type of controller is not very sensitive to the vehicle configuration and its dynamics. According to the authors of that work, the benefits of using this type of controller are:

Simplicity, because a dynamic model of the system is not required; the control strategy best fits the control objectives and constraints; by using linguistic rules you can have easy understanding and manipulation of the controller. In [84] genetic algorithms were applied to tune rules for a fuzzy logic controller. Experimental tests were carried out and it was shown how the controller adjusted by the genetic algorithm improved its performance. On the other hand, in [85] the application of a controller in sliding modes with fuzzy logic was presented.

5. WIRELESS COMMUNICATION IN UNDERWATER ROBOTS

Like submerged communication, it presents unique challenges compared to other forms of communication, but it affects the operation of multiple robotic systems (MRS). There are generally four types of underwater communication channels: acoustic, radio frequency (RF), optical, and magnetic [86, 87].

5.1 Audio Communication

The acoustic method is widely employed in underwater communications. Communication can be sustained at distances ranging from tens of meters to tens of kilometers [88, 89]. Location-based voice communication is utilized in numerous applications, such as video monitoring within the vicinity (as described in the second part). Moreover, voice communications may encounter considerable delays attributable to slower voice transmission speeds [90, 91].

5.2 Radio Frequency (RF) Communications

It is effectively transmitted via radio waves across the visible air/water spectrum, making it robust for MRS applications in cloudy weather [86]. Consequently, water affects radio transmission waves, if one of its transmissions reaches an animal specified with dimensions not exceeding 10 M in the second one [92, 93].

5.3 Visual communication

It’s possible that wireless communication could achieve increased connectivity over decades, but it requires greater transparency for many years. The life suspended there and the universe in the ocean is most destroyed by the talk of your presence. To facilitate this, Bahthon uses modern yellow or green-green, water-resistant machines. From 1 to 10 responses in the second, no distance could be crossed for 100 meters [94-96].

5.4 Interface with magnetic sensors

Interaction has been studied by magnetic detection, another technique, in laboratories [97], It provides additional stability and stability on the tank due to the competing magnetic efficiency of water and air [98].

Table 4: presents a comparison between these communication methods, characterized by.

Communica-tion Method	Range	Rate	Limitations
Acoustic	Dozens/hundreds of meters to several/dozens of kilometers	Several tens of kbps	Underwater background noise, signal attenuation, high delay
RF	Few meters	Up to 10 Mbps	RF waves absorbed by water
Optical	Tens of meters	1-10 Mbps	Requires high water transparency, affected by suspensions and organisms in seawater
Magnetic Induction	Laboratory settings only	Stable and predictable	Limited research and application

By understanding the strengths and limitations of each approach, researchers and engineers can select the most appropriate communication technology in their underwater robotic systems

6. CONCLUSIONS

The objectives of this work were twofold: on the one hand, to present educationally the different topics revolving around underwater robotics, and on the other hand, to review the state of the art of this field of robotics.

Applications of underwater robotics are described and classified. Next, the types of components typically found in underwater robots (cabin, sensors, propulsion systems, robotic arms, and power sources) were presented. The derivation of the equations of motion is briefly presented. Particular emphasis was placed on this topic because in underwater robotics, velocity and its time derivatives are measured concerning the body's frame of reference. In addition to Section 4, a review of control strategies that have been proposed for underwater robots is presented. Finally, in Section 5 we explored different methods of, underwater communication, including acoustic induction, radio frequency (RF), and optical and magnetic induction, as used to understand the strengths and limitations of different, communication methods.

The reference book on marine ship modeling and control is the one presented in [68]. There you can find modeling of waves and sea currents. In addition, this reference covers different types of controllers applicable to underwater robots. On the other hand, in [85] a review of the control situation of marine vehicles was performed. Regarding the topic of controlling robots with maneuvering arms, Reference [99] presents the application of different techniques to this control problem. On the other hand, [100] presents a theory for calculating the hydrodynamic parameters of solid bodies in water. Here are some recommended recent reviews for your reference: [10, 20, 101]. Underwater robots have dramatically changed the process of seafloor exploration. In addition, these robots have made it possible to carry out interventions in disaster situations such as leaks in oil facilities. Specifically, the maintenance of oil and gas extraction facilities located in deep waters is what will force the extensive use and improvement of underwater robots. There is no doubt that the development of this technology is important given the current needs and potential future applications of these robots.

Abbreviations

AUVs	Autonomous Underwater vehicles
ROVs	Remotely Operated Underwater Robots
IAUVs	Intelligent Autonomous Underwater Vehi
UUV	unmanned underwater vehicles
TMS	Tether-Cable Management System
PVC	Polyvinyl Chloride
GPS	Global Positioning System
IMU	Inertial measurement unit
SSC	Solid state compass
CG	center of gravity
DVL	Doppler velocity log
LBL	Long Baseline Systems
SBL	Short-Baseline System
USBL	Ultra-Short Baseline Systems
SLAM	Simultaneous Localization and Mapping
MHD	Magneto hydrodynamic Impeller
LMI	linear matrix inequalities
PID	proportional–integral–derivative
MCS	Mission Control System
NED	North-East-Down
MRS	multiple robotic systems
RF	radio frequency

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روبوتات تحت الماء: مبادئها، مكوناتها، النمذجة، والتحكم

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الملخص

نظم الروبوتات تحت الماء قد غيّرت بشكل كبير مجال استكشاف أعماق البحار عن طريق تمكين العمليات المختلفة في المنشآت البحرية البعيدة. مما جعل مستقبل هذه التكنولوجيا واعد للغاية. تهدف هذه الدراسة إلى تقديم فهم عميق لموضوع الروبوتات تحت الماء لطلاب الدراسات العليا والمهندسين والباحثين الذين لديهم اهتمام في مجال الروبوتات تحت الماء. وبالإضافة إلى ذلك،يشمل هذا العمل دراسة شاملة للمجالات المتنوعة المتضمنة في مجال الروبوتات تحت الماء.

الكلمات الداله :
تكنولوجيا تحت الماء ، مكونات الروبوتات، النمذجة، والتحكم، مسح المجال، العمليات عن بعد ، الاتصالات اللاسلكية المدمجة.