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State of the Art of Parameters for Mechanical Design of an Autonomous Underwater Vehicle

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Abstract

This work presents a guide for researchers interested in Ocean Engineering and Underwater Robotics design of Autonomous Underwater Vehicles (AUV). The main purpose of this review is to evaluate the present situation of underwater robotics; specifically of AUV´s, in this review we integrated several existing AUV´s. Data analysis was taken from 33 AUV´s belong to sixteen different countries around the world, these AUV's have been study in 40 groups in universities, research institutes and business companies.

The state of the art is based on three main aspects: mission developed by the AUV's, conditions of operation and design of the hull. With this review the reader will have important information about AUV's; such as typical speed, maximum operating depth, navigation and communication systems, shapes and materials used in hull manufacture.

Based on this work, researchers in ocean engineering and robotic underwater, has the possibility to define parameters of operation of the AUV that wants to design, taking into account the type of missions they want to develop. The parameters used by other researchers will serve as a starting point for your own design and research, with that you will overcome the difficulties that other projects had to overcome. In this work are included all the possibilities of use of an AUV, for any design. All the information contained in this work has updated with the most recent published papers of each AUV.

Keywords: Ocean Engineering, Underwater robotics, AUV, Mechanical design, hull shapes, hydrodynamics.

INTRODUCTION

Around 75% of the surface of the planet is water; thus lakes, oceans, rivers and other water bodies is very important field of study. The underwater environment has many conditions impossible to be access by a human, e.g., high hydrostatic pressure is one of the main inconvenient. Other difficulties for human access are low temperature and dangers related to different animal species in water.

AUV´s are one of the main tools in development of underwater research, many of the results obtained in this research area have been made possible by the new technologies incorporated in the AUV´s. Improvements in electrical components and new materials have greatly contributed to the progress of underwater robotics.

In order to redesign or to plan a new design should include the experiences multidisciplinary research groups who have been directly involved in important areas such as hydrodynamics (hull's geometry), materials and manufacture and, operation; fields that can be taken in to account to redesign or design AUV´s.

MATERIALS AND METHODS

Data review were obtained from 33 AUV´s from sixteen different countries, 40 research groups belonging to universities, research institutes and business; from all this information, eight mechanical design parameters were obtained.

All information data was based on specialized databases in engineering topics such as ScienteDirect, IEEE and Springer, documents were also collected from specialized literature in underwater vehicles such as EurOcean_UV (European Underwater Vehicles Infobase), AUVAC (Autonomous Underwater Vehicle Application Center). Mechanical design was the main theme of the articles consulted; this option was made in order to define the design trends implemented in the main AUV´s.

Worldwide, the countries that stand out in development of AUV´s are China and the United States, in Europe countries like France, Germany, Spain, United Kingdom, Italy and Portugal. Other countries that also have worked in this topic are Russia, Canada, Australia, India, South Korea, Brazil and Mexico.

Figure 1 show worldwide countries distribution used for state of the art review for this paper work.

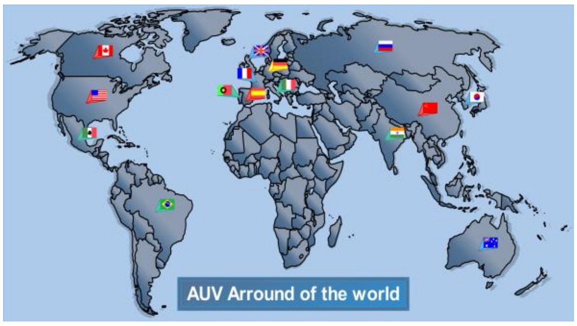

Figure 1. AUV´s arround or the world

Table I presents a list of AUV´s used to develop the analysis the main design parameters; which is the core of this article.

Table 1. AUV´s used for data analysis

Name	**Geometry**	**Depth (m)**	**Speed (m/s)**	**Mision**	**Material**	**Volume size (m^3)**
ALBAC	Torpedo with flippers	300	1.03	Research	Aluminum	0.57
Alistar 3000	Drop type	3000	1.03	Commercial	Aluminum	12.10
Alister REA	Torpedo	300	4.12	Surveillance	Aluminum	2.35
Aqua Box II	Oval type	50	1.00	Research	F. glass	0.86
Aqua Explorer 2	Torpedo	2000	2.80	Commercial	F. glass	3.51
Aqua Jelly	Biomimetic type	20	0.30	Commercial	Aluminum	0.02
Aqua Penguin	Biomimetic type	50	2.70	Commercial	F. glass	0.10
Autosub 6000	Torpedo	6000	2.00	Research	Aluminum	4.46
Autosub 1600	Torpedo	1600	2.00	Surveillance	Aluminum	5.67
AUV-Gilder	Open structure type	4000	0.98	Research	Aluminum	1.78
Bionik Manta	Biomimetic type	100	2.78	Commercial	Aluminum	2.63
Bluefin-12	Torpedo	200	2.57	Surveillance	Aluminum	3.76
Bluefin-9	Torpedo	200	2.06	Research	Aluminum	0.10
Charybdis	Disk type	20	0.70	Research	ABS	0.91
Gavia	Torpedo	1000	3.00	Surveillance	Aluminum	0.11
Hammerhead	Torpedo	100	2.50	Research	Aluminum	0.27
Infante	Rectangular type	500	2.50	Research	F. glass	5.13
LAUV	Torpedo	50	2.50	Surveillance	Aluminum	0.03
Liberade	Delta wing	100	0.80	Surveillance	F. carbon	0.71
Mako	Open structure	50	2.10	Research	Aluminum	0.17
Manta	Biomimetic type	800	5.14	Surveillance	F. carbon	22.9
Maya	Torpedo	200	2.30	Commercial	Aluminum	0.09
Morpheus	Rectangular type	200	2.57	Surveillance	F. carbon	0.09
Odyssey IV	Drop type	6000	2.00	Research	F. carbon	0.75
REMUS 100	Torpedo	100	2.60	Surveillance	Aluminum	0.06
SAUV II	Torpedo with flippers	500	1.54	Commercial	F. glass	1.27
Sea Squirt	Torpedo	200	1.54	Research	ABS	0.07
SeaOatter MK II	Oval type	600	2.30	Research	F. glass	1.62
Serafina	Torpedo	20	1.00	Commercial	Aluminum	0.01
SPRAY	Torpedo with flippers	1500	0.26	Research	Aluminum	0.08
Taipan 2	Torpedo	100	1.80	Research	Aluminum	0.07
Tuna-Sand	Open structure	1500	1.29	Research	F. carbon	1.10
Virginia Tech	Torpedo	100	2.30	Research	Aluminum	0.01

AUV´s AND THEIR MISSIONS AND APPLICATIONS

It is very interesting to observe the diversity of activities that are currently carried out through AUV´s, these vehicles have become the most successful solution for multiple applications, and also, many of these activities today would not be possible without the use of AUV´s, primarily because these activities involve human risk. If you wish to make an AUV classification based only on the activities they develop, we could say that there are three main types: research, commercial applications and surveillance applications.

In the first category, AUV´s are used mainly by research groups from universities and companies in areas such as underwater robotics, Offshore research, marine sciences, marine chemistry, marine physics, marine geophysics, marine geology, interstitial water, marine biogeochemistry, marine biology, marine ecology, marine environment, marine pollution, trace organic contaminants, coastal disaster, radionuclides, atmospheric deposition, marine aerosol, sea surface microlayer, air-sea exchange processes, mangroves, coral reefs, marine meteorology, hydrodynamics, coastal and ocean dynamics, ocean engineering, beach erosion, remote sensing application, geographical information system, water system modeling, coastal modeling in estuaries, coastal zone management.

In the second type AUV´s are used in commercial applications, for example, fisheries, aquaculture, fishery economics, fishery management, petroleum engineering, platforms underwater petroleum of drilling, port engineering, naval engineering, telecommunications engineering and submarine cable supervision.

The last category of AUV´s are used in military industry since they are used in surveillance activities, search y recovery applications, launch y recovery systems.

A. AUV used in research applications

Figure 2 presents the percentage of AUV used in research; this graph shows that 48% of the AUV´s are used in research, i,e., 16 of 33 AUV’s.

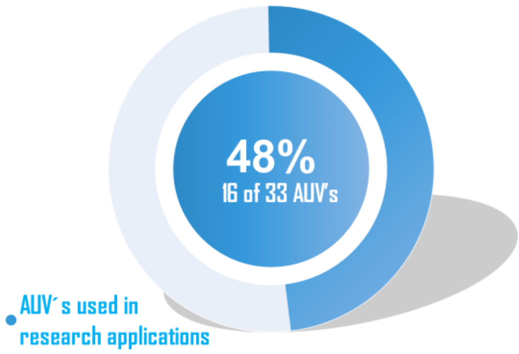

Figure 2. Percentage of AUV´s used in research

In regard to underwater research, AUV are an essential tool to obtain samples for research projects, to do this by humans are impossible mainly because of the high hydrostatic pressure which force to use equipment of high technology in order to support huge hydrostatic pressure.

AUV´s have been used in research missions such as environmental monitoring and oceanographic exploration, in some cases, sea water samples have been taken to analyze the salinity of the sea at the point where the lagoon of the “Smallest Sea” and the Mediterranean Sea or the “Largest Sea” converge in Murcia, Spain [1].

Phytoplankton has an important impact in the ocean ecosystem, as a result of past investigations an adaptive activation method was developed using an AUV, this method allows to capture samples of water in the Monterey Bay, when there are peaks of fluorescence chlorophyll in a thin phytoplankton layer; the data analysis showed the impact on productivity patterns, survival and larval growth [2].

B. AUV used in commercial applications

In Figure 3 the parentage of AUV used in commercial missions are presented, these date shows that 9 of the 33 AUV included in this article are used in category, which represents a 28%.

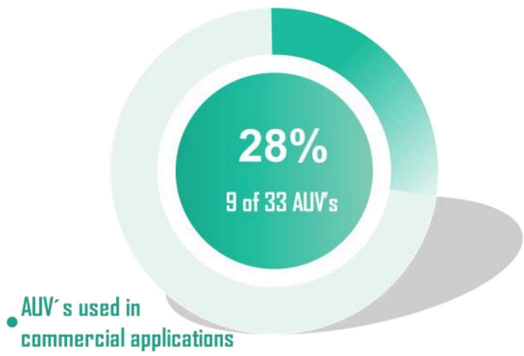

Figure 3. Percentage of AUV´s used in commercial applications

Search for energy resources has raised the exploration of environments of extreme conditions for humans, e.g., the exploitation of oil sources on platforms in the sea, the exploitation of these resources demands the implementation of efficient transport means for raw materials, for example heavy submarine pipelines. On the other hand, in telecommunications, one of the most up-to-date developments is real-time communication applied worldwide, for this application an underwater net optic fiber has been made. These two commercial activities require every day supervision, so AUV´s are used to task these activities. AUV´s are also applied in preventive and corrective maintenance and, inspection activities.

Specific research developed for oil and telecommunications companies have been reported in literature, e.g., an AUV equipped with auto-tracker, technology plus sensors like a lateral search sonar, a geo-positioner, an inertial navigator and a shape recognizer based on artificial neural networks, so through the simulations of the algorithms of each module, this was incorporated into the physical part of the AUV to perform tests in real environment [3].

Hazard underwater environments are difficult to access not only for humans, but also for AUV´s; an AUV can be trapped during missions, exploring for a solution to this problem, research on a state machine named auto-tracker module have been done, in this module software in C++ language has been implemented and by estimating the error between the position of the AUV and inspected element, for example, pipeline or cable, achieved a better precise positioning of AUV, but it has limitations in decision making [4].

C. AUV used in surveillance applications

Percentage of AUV´s used in surveillance missions are showed in Figure 4, this type of AUV´s represents a 24% of the AUV´s studied in this work.

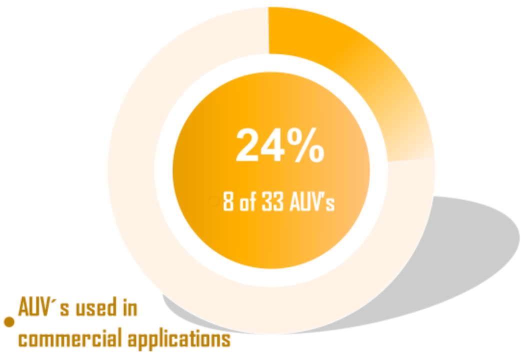

Figure 4. Percentage of AUV´s used in surveillance applications

Underwater environment is unpredictable due to frequency variation of weather conditions, on most occasions military missions have a very high level of danger, If this is added to the atmospheric conditions exist a high probability that a military mission to fail, for this reason, research was focused on the collection of data related to the environmental conditions of different areas, this information helped to simulate the conditions that can be found in these environments at the time of carrying out military missions [5].

The autonomy of AUV´s are represented by two aspects: number of hours of work without needing any assistance and the ability to made decisions to carry out a mission. The autonomy is an important feature in surveillance missions, research has been carried out where new control architecture was proposed to meet the terms with aspects of autonomy referring to the decision making in the missions in which the AUV´s initially lacks information. Control designed in this research, is a hybrid control that uses the management of individual tasks, and manages an elaborate plan that consists in activating and deactivating the navigation strategies according to the progress of the mission [6].

CONDITIONS OF OPERATION OF AUV´s

Each AUV to achieve its mission should fulfil different requirements, according to the previous classification: research, commercial, surveillance. For example a mission depth is an important parameter in research and commercial missions and, speed is a key feature in surveillance missions.

A. Maximum Operating Depth

Exists a direct relationship between hydrostatic pressure and operation depth, pressure is directly proportional to depth, pressure is a parameter that directly influence materials and geometry of the AUV´s. Typical range of depth operation varies from zero to 6,000 meters [7].

Discovering and analyzing the underwater environment is the main purpose of research missions, depth range of immersions it is wide like the ocean itself, there are analyzes focused on the research area, developed between zero and 100 meters, being this range the least deep and between 3,000 and 6,000 meters the deepest. On the other hand, commercial activities developed by AUV's are made in ranges that do not reach so much depth. In the case of surveillance missions are carry out at shallow depth.

In Figure 5 depth ranges are presented being the most common between zero and 100 meters with 38 % (13 AUV's), follow for a 31 % (10 AUV's) of a range between 101 and 500 meters. One should note here that 69% (23 AUV´s) of the missions are developed between zero and 500 meters.

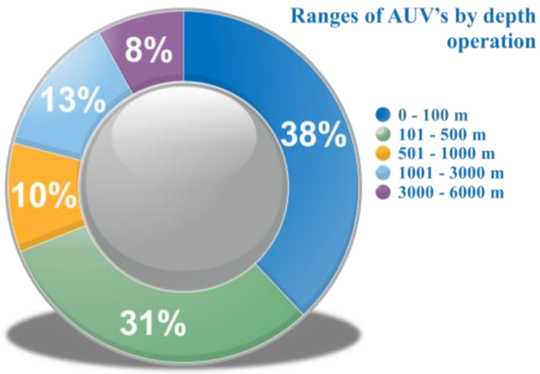

Figure 5. Ranges of AUV's by depth operation

B. Maximum speed

Hull's geometry of the AUV's influences the maximum speed of displacement, surveillance missions require that AUV's achieve high speed since it is necessary to reach places in a minimum time; they also develop hunting missions that require high-speed conditions. On the other hand, research and the commercial missions involve low-speed, as the task is to sample the underwater environment or to checkup underwater facilities. Speed range for AUV's is between 1.1 m/s and 7 m/s. [8]

Figure 6 show percentages of speed ranges for AUV's, AUV's with a speed range between 2.1 and 3 m/s represent a 44 % (14 AUV), only 10 % (3 AUV) move at higher speeds. Most of missions are performed at speeds below 3 m/s (90 %).

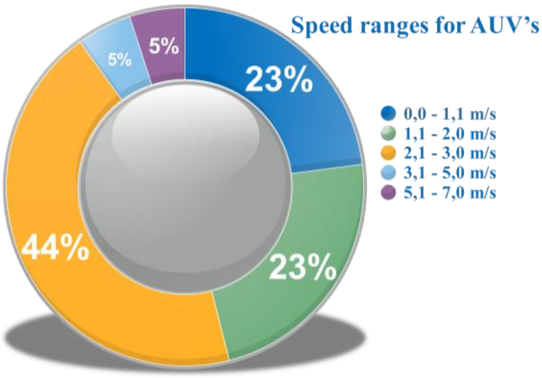

Figure 6. Speed ranges for AUV's

C. Communication and Navigation Systems

Since AUV's are unmanned vehicles, although they have cameras, there is no transmission of images or information in real time, so in most cases navigation is blindly performed. Acoustic systems avoid possible collisions either against obstacles or sea bottom, this ability is known as "situational awareness". [9]

The communication based on electromagnetic waves is eliminated when AUV's are submerged; therefore they used other methods of communication between the base station and the AUV's. In aquatic environment, acoustic communication is the most effective method, some programs and research groups have evaluated other methods, such as those based on low laser frequency; which are cleaner and robust against noise or external disturbances. Now a days acoustic systems that offer radiofrequency based communication with a relatively low error can be found. In the last 10 years we have reached thousands of samples per second with a few Kbps, this area of the AUV's continues in active research for several groups. [10]

To improve AUV's navigation a system call inertial navigation have been incorporated, this system sometimes is combined with sonar systems and offer better precision and high speed, but these technologies are still very expensive. Another technique incorporated into the AUV's navigation is GPS system, this allows positioning and control AUV's trajectory, and the main drawback of this system is the need to periodically reach the surface to update position data. Sometimes acoustic sensors with GPS trajectory control are combined. [11]

As the robotics started to work in underwater research, this area generated a universe of requirement due to changing environmental conditions, existing sensors used in aerial and terrestrial environments, which are not subject to the very demanding conditions that are present in the submarine depth, such as: corrosion, low temperatures, high hydrostatic pressures, low visibility, all with the need for absolute water tightness. The term LENS "Longer and Longer Ranges" that encompasses the sensors that allow a high resolution in a long range, is a feature that can be seen in several of the products currently offered. [12] Electronics companies dedicated to the design of sensors focused their efforts on this new range of submersible sensors, some of the most relevant parameters are: versatility, speed, low energy consumption and size of the censors applied to AUV's. [13]

AUV HULL DESIGN

AUV's material is undoubtedly one of the main components, in first place, provides a watertight compartment where the electronics are housed, at the same time must resists the hydrostatic pressure and also contribute to drag force. [14]

Hull's material and shape are combined to optimize the performance of the AUV's reducing the energy consumption with geometry and material that generate low drag force in its displacement.

A. AUV's hull shapes

There are AUV's missions where speed is very important, for example, the surveillance missions require fast AUV's, thus it is essential to design AUV's with low drag coefficients and high speeds [15]. Some of common AUV's geometries are: Torpedo, Torpedo with flippers, open structure type, Biomimetic type, rectangular type, Oval type, drop type, delta wing type and disk type.

Figure 7 shows different forms of AUV's hull, torpedo geometry represents 42% which means that 33 of AUV`s analyzed have this geometry, this geometry is the easiest to manufacture compared with the other AUV's geometries..

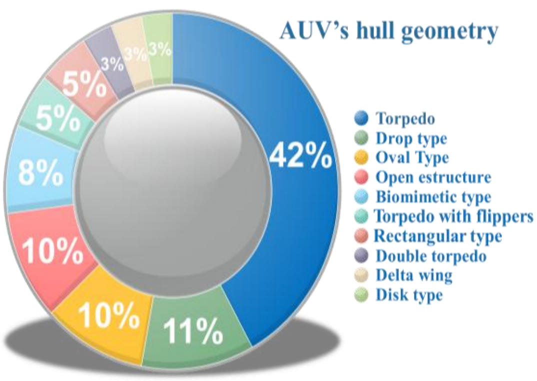

Figure 7. AUV's hull geometry

Design of the hull's geometry is one of the main factors to decrease or increase drag coefficient of the AUV, hull geometry like a drop type of water generate low drag forces compared with the other geometries. This geometry is generated by an ellipsoid and a paraboloid. [16]

B. Material used in the manufacture of AUV´s hull

In order to choose the right material, depth of operation, shape and size must be taken into account, balance between these characteristics can generate a good AUV design that fits the mission requirements. Some of the materials used to build the AUV's hull are: Aluminum, Fiberglass, Carbon Fiber and Acrylonitrile Butadiene Styrene (ABS). [17] [18] [19]

In Figure 8 represented graphically the distribution of the materials used in the manufacture of AUV's hull.

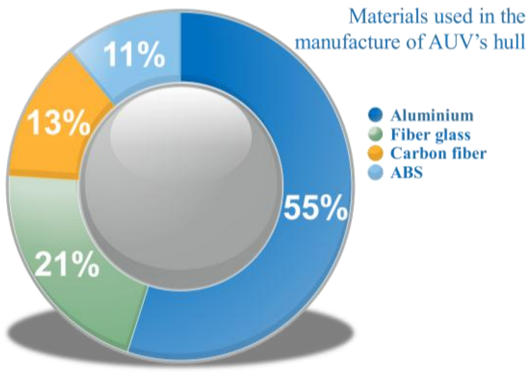

Figure 8. Materials used in the manufacture

SOME CURRENT AUV's

Literature report several AUV's geometry designs: *Liberdade* with a delta wing geometry is used in missions of surveillance, inspection and tracking [20]. *Aqua Jelly* is a biomimetic type design used in commercial missions, inspection [21]. *Aqua Penguin* also with biomimetic type design is used in commercial missions, inspection. [22]. *Bionik* has a geometry design manta ray used in commercial missions, environmental monitoring, hydrographic studies, marine deep mapping, finding and recovery [23]. *Glider* has a like water drop type geometry design and is used in missions of research, environmental monitoring, geophysical study, marine science studies, oceanographic studies and, scientific investigations [24]. *Mako* is an open structure type used in missions of research and oceanographic studies [25]. *Tuna-Sand* is a open structure geometry design and its missions are research and marine deep studies [26]. *Alistar 3000* with a like water shape drop is used in commercial missions, inspection of pipelines and submarine cables [27]. *Odyssey IV*, has a geometry design in like water drop shape its missions are research and oceanographic studies. [28]. *Aqua Box II* design in oval type geometry is used in research and coastal mapping [29]. *Manta*, has biomimetic type design is used in missions of surveillance and vehicle test [30]. *Infante AUV*, has been design rectangular type geometry shape is used in missions of research, oceanographic studies [31]. *Morpheus*, is also a rectangular type AUV, is used in missions of research and oceanographic studies [32]. *Alister REA*, has a design in shape of torpedo and is used in missions of surveillance, mines and ships finding, marine deep mapping and, environmental evaluation [33]. *Aqua Explorer 2*, has a design in shape of torpedo, is used in commercial missions, study of fishing resources and marine biological studies [34]. *Autosub 6000* designed in torpedo shape, is used for research, environmental monitoring, geophysical, marine science and oceanographic studies [35]. *Autosub 1600*, has a design in geometry of torpedo, is used in missions research, environmental monitoring, geophysical, marine science and oceanographic studies and, scientific investigation [36]. *Bluefin-12*, has a design in shape of torpedo, is used in missions of surveillance, safety in ports and coasts, hydrographic studies, seabed mapping [37]. *Bluefin-9*, has a geometry design of torpedo, is used in missions of surveillance, safety in ports and coasts, hydrographic studies, seabed mapping [38]. *Gavia*, has a design in shape of torpedo, is used in missions of research, environmental monitoring, geophysical, marine science and oceanographic studies and, scientific investigation [39]. *Hammerhead*, has a design in shape of torpedo, is used in missions of research, hydrographic study, development of sensors, search vehicle. [40] *LAUV*, has a design in shape of torpedo, is used in missions of surveillance, finding for mines and ships, marine deep mapping, environmental evaluation. [41] *Maya*, has a design in shape of torpedo, is used in commercial missions, study of fishing resources, marine biological study. [42] *Remus 100*, has a design in shape of torpedo, is used in missions of research, scanning by scavenging, conductivity data, temperature and depth. [43] *Sea Squirt*, has a design in shape of torpedo, is used in missions of research, hydrographic study, development of sensors, search vehicle. [44] *Serafina*, has a design in shape of torpedo, is used in commercial missions, exploration and control. [45] *Taipan 2*, has a design in shape of torpedo, is used in missions of research, oceanographic study. [46] *Virginia Tech*, has a design in shape of torpedo, is used in missions of research, tracking activity, seafloor scanning. [47] *ALBAC*, has a design in shape of torpedo with flippers, is used in missions of research, marine deep study. [48] *SAUV II*, has a design in shape of torpedo with flippers, is used in commercial missions, search vehicle. [49] *SPRAY,* has a design in shape of torpedo with flippers, is used in missions of research, Oceanographic study. [50]

CONCLUSIONS

AUV’s with better hydrodynamic geometries impact directly on two important aspects: speed and energy, with higher speed they can achieve their missions in shorter time, this is directly involve in energy saving; this two factors increase AUV’s autonomy, thus more working hours without stopping to recharge the power source. AUV’s with hydrodynamics geometries allow to reach the highest speed because their low drag coefficient. Literature review showed that drop type and torpedo type geometries are the more common.

On the other side, analyzed information showed that aluminum and fiber glass are the most commonly materials used, with 55% and 21%, respectively.

Based on mission characteristics literature review showed that the average speed velocity range between 2 and 3 m/s. This parameter is an important condition for determining a propulsion system power.

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