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Application of the Analytical Hierarchy Process for the Selection and Deployment of Deepwater Search and Rescue Vehicles

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ABSTRACT

The Spanish Navy is immersed in a process of modernisation and acquisition of new naval systems, such as S-80 submarines and a BAM-IS (Underwater Intervention Maritime Action Vessel) underwater intervention vessel, and in this regard, technological advances require increasing the capabilities of submarines for rescue and salvage operations. The study investigates the potential benefits of a submersible compared to a remotely operated vehicle or an autonomous system using the Analytical Hierarchical Process (AHP) method devised by Thomas L. Saaty.
This empirical study provides an objective evaluation and comparison of the key criteria involved in choosing a vehicle that is suited for use at great depths, while considering the specific needs and requirements of the Spanish Navy. The evaluation criteria include many elements such as mobility, operational depth, cargo capacity, autonomy, and human-machine interaction. Although still in the developmental stage, autonomous systems possess specific characteristics that make them well-suited for submarine rescue missions.

1. Introduction.

Amid ongoing worldwide geopolitical shifts, the Law of the Sea has been impacted in relation to portions of the seabed that lie outside the jurisdiction of any particular nation. Technological advancements enable humanity to exploit deep resources, including precious minerals, hydrocarbons, genetic biological material, and strategically significant locations for military stations (Conte de los Ríos, 2023). According to the 2021 National Security Strategy, military capabilities associated with deterrence and defence must provide credible deterrence, effective response across the spectrum of crisis, or conflict, and must be sustainable over the long term (DSN, 2021).

The National Strategy for Maritime Security 2024, emphasizes that the constraints in utilizing specific terrestrial resources and the increased understanding of the opportunities presented by the marine environment drive a rising pursuit for alternatives in the sea, including the valuable resources found in the seabed. This competition for access to these resources is a significant factor. These actions can result in intentional behaviours that endanger the ecological health of the marine environment, such as the unsustainable and unlawful exploitation of natural resources, which are seen as a risk to maritime safety. Furthermore, the utilization of autonomous marine vehicles (including those that operate in the air, on the surface, or underwater) is highlighted as a means to intentionally carry out unlawful activities. This has emerged as an escalated concern due to their adaptability and the ease with which they may be obtained and operated (DSN, 2024).

Thus, considering the current strategic framework, it is recommended to prioritize programs aimed at enhancing capacities for exploring and understanding the seabed. The focus will be on acquiring capabilities related to maritime intervention and action, surveillance, control, protection, damage assessment, and evidence collection in the underwater domain. These capabilities will be aimed at ensuring the security of crit-

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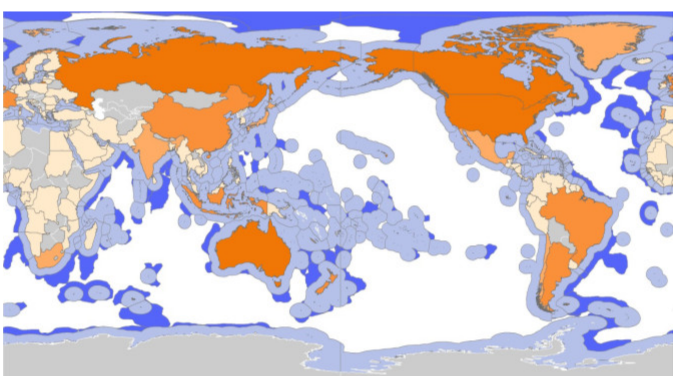
ical underwater infrastructures and other essential infrastructures. Additionally, measures to address the criminal use of underwater vehicles, semi-submersibles, or remotely operated devices will be encouraged. Furthermore, Spain will reinforce self-governance in the planning, building, running, and upkeep of the essential naval and port units and infrastructure. This includes the advancement of the new remotely operated anti-submarine system project in the framework of the European Union's Permanent Structured Cooperation (PESCO), and participation in NATO's unmanned submarine vehicle acquisition programs (Ljulj, Slapničar and Smiljanić, 2024).

2. Objectives.

In the near future, advancements in technology will enable us to easily access and utilize any location in the ocean, regardless of its depth. These figures indicate that 95% of the world's habitat remains unexplored, with 80% of it yet to be investigated. The international community has initiated formal discussions for a legally binding agreement to conserve and sustainably utilize biodiversity in maritime areas beyond national jurisdiction (ABNJ) due to the enormous increase in pressure on these areas in recent decades (Wright *et al.*, 2021) and the significance of the high seas as we can see in the Figure 1.

Figure 1: High Seas Zones.



Source: Project GEBCO.

Hence, the authorities have shifted their focus towards the waters situated in regions beyond national jurisdiction, where it is approximated that numerous species, numbering in the millions, reside. These genetic resources serve not only as sources of food, but also as foundations for the development of novel treatments and health goods that can yield significant advantages (Ramos, 2019). To protect resources, each nation must design effective compliance and enforcement mechanisms, and engaging adequately with relevant stakeholders in order to mitigate the effects of deep sea mining and the harvesting of marine genetic resources (De Santo, 2018). With the adoption of the "High Seas Treaty"[4], it aims to limit the uncontrolled exploitation of genetic and mineral resources. Given that military submarines serve as the primary means of covert surveillance to safeguard important seas, it is imperative to enhance search and rescue capabilities in the event of a distressed submarine (DISSUB) crisis (Pereira *et al.*, 2024). In order to accomplish this, we want vehicles that possess the capability to function at significant depths underwater. The vehicles selected can be classified into three primary categories: DSV (Deep Submergence Vehicle), ROV (Remotely Operated Vehicle), and AUV (Autonomous Underwater Vehicle).

A DSV, is a manned submersible designed to operate at great depths in the ocean. These vehicles, are typically equipped with advanced sensors, control systems, and data processing capabilities to aid in underwater exploration, research, and rescue missions. DSVs often have a spherical pressure hull, like the one in Figure 2, to withstand immense water pressure (Khan and Sohail, 2025) and are outfitted with external manipulator arms, cameras, and scientific instruments. They rely on inertial navigation, velocity measurements, and position data from various sources to navigate and operate precisely at extreme depths (Jiang *et al.*, 2023).

Figure 2: DSV Aurelia.

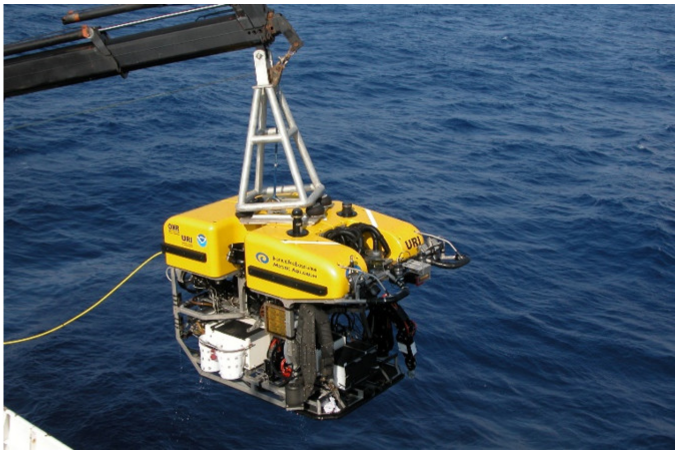
Source: REV OCEAN.

A marine ROV, is an unoccupied underwater robot that is controlled and powered from a surface vessel or platform. It is connected to the surface by a tether or umbilical cable that provides power, video, and data transmission, and all of this is controlled from the command centre located on the ship where the deployment takes place (see Figure 3). ROVs are highly manoeuvrable and can be equipped with various tools and sensors, making them ideal for underwater exploration, inspection, maintenance, and research tasks. They are widely used in offshore oil and gas operations, scientific research, search and rescue missions, and maritime archaeology (Konoplin *et al.*, 2022).

Autonomous Underwater Vehicles (AUVs), are unmanned, self-propelled submersible vehicles used for various underwater applications. They have different hydrodynamic shapes and generally converge in the torpedo-like profile (see Figure 4)

[4] Although it is known as the "High Seas Treaty", the full and more correct name is: "Intergovernmental Conference on an International Legally Binding Instrument relating to the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity in Areas beyond National Jurisdiction". This treaty allows for the very important exploitation of marine genetic resources and mining.

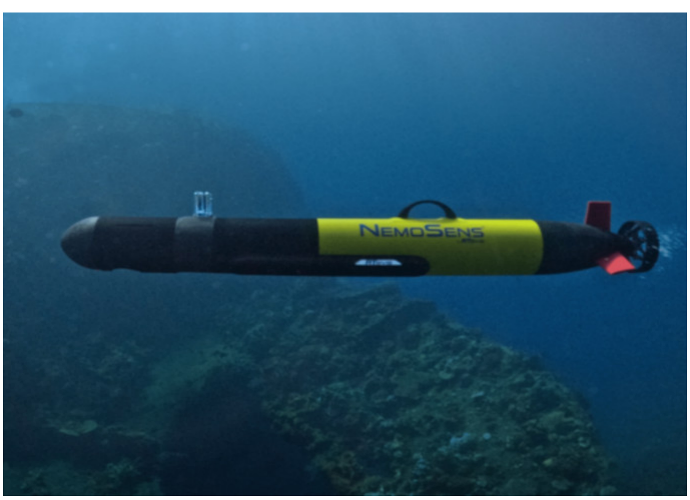
Figure 3: ROV Hercules deployment.



Source: Nautilus Oceanica.

needed to be able to operate at great depths. Also, they are equipped with sensors, cameras, and navigation systems to operate autonomously without human intervention. Key applications of AUVs include environmental monitoring, oceanographic surveys, underwater infrastructure inspection, mine countermeasures, and search and rescue operations. AUVs offer advantages such as reduced risk to human life, access to harsh environments, and cost-effectiveness compared to traditional manned underwater vehicles (Nicholson and Healey, 2008).

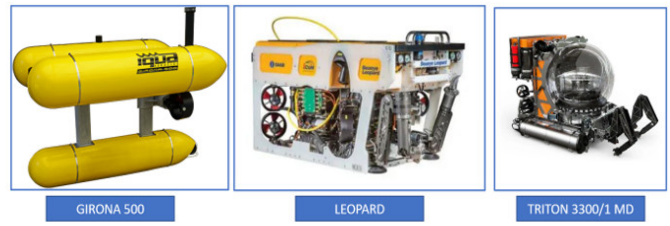
Figure 4: AUV Nemosens.



Source: RBR GLOBAL.

Once the three types of vehicles have been presented, we will move on to the objective and the models selected for the study. The objective of this study, is to obtain, in a quantitative and measurable way, the advantages of each of the three types of underwater vehicles described, and to analyse if it is necessary to include a DSV as a future need for the Navy, which already has an ROV (Leopard) and an AUV (Girona 500), for this reason a multi-criteria analysis will be carried out, adding the DSV vehicle that the Navy currently has, and that has already operated in tests (TRITON 3300/1). Regardless of the photographs in figure 5, the real size difference between each of the underwater vehicles is quite significant, with the vehicles ordered from smallest to largest starting from the left.

Figure 5: Vehicles selected for the study.



Source: Authors.

3. Methodology.

The Analytical Hierarchy Process, known as AHP, is a systematic method that utilizes mathematical and psychological principles to effectively organize and analyze intricate decision-making processes. The method was devised by Thomas L. Saaty during the 1970s and has undergone thorough examination and enhancement ever since. The AHP assists decision makers in identifying the most suitable solution based on their objectives and comprehension of an issue, rather than imposing a definitive ”right” answer. The framework offers a thorough and logical structure for organizing a decision problem, representing and measuring its components, connecting those components to overarching objectives, and assessing several solutions (Ashour and Mahdiyar, 2024). The procedure comprises three primary stages.

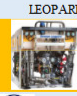
Begin by structuring the problem as a hierarchy, which consists of the decision goal at the top, followed by the alternatives for achieving it, and finally the criteria for assessing the alternatives. Next, determine the order of importance among the items of the hierarchy by evaluating them through a series of comparisons made in pairs. When evaluating potential investments in commercial real estate, investors may prioritize location over price and price above timing. Lastly, combine these evaluations to get a collection of ultimate priorities for the hierarchy. This would amalgamate the investors' assessments of the location, price, and time for properties A, B, C, and D into comprehensive priorities for each property (Saaty and Vargas, 2012).

t AHP transforms evaluations into numerical values that can be analyzed and compared across the entire spectrum of the problem. A numerical weight or priority is assigned to each member of the hierarchy, enabling the comparison of varied and frequently incomparable elements in a logical and consistent manner. This feature sets the AHP apart from other decision-making methods. During the last stage of the procedure, numerical priority is computed for each of the choice alternatives. These numbers indicate the comparative effectiveness of several options in achieving the desired outcome, enabling a clear evaluation of the available courses of action. AHP is particularly valuable in situations where groups of individuals are collaborating on intricate issues, particularly those that carry significant consequences, encompassing human perspectives and evaluations, and whose outcomes have enduring impacts. It offers distinct benefits in situations when crucial aspects of the choice are challenging to measure or compare, or when team members' diverse expertise, terminology, or opinions hinder effective communication, and are tackling intricate problems that have significant consequences and require human judgment.

Although it may also be utilized by individuals for simple decisions, its true potential lies in addressing complicated problems with long-term implications. AHP not only facilitates decision makers in reaching the optimal conclusion, but also offers a transparent justification for the selected choices. To carry out this evaluation, a group of experts working on the S-80 Program, both from the Spanish Navy and Navantia, who are fully aware of the problems and difficulties involved in submarine navigation, have been selected.

The first thing we have to do is to draw up a comparative table, as shown in the Figure 6, which presents a detailed analysis of the criteria we want to analyze for the three vehicles: the ECA Girona 500, the SAAB Leopard, and the Triton 3500 IMD. Each of these criteria/sub-criteria represents a different trade-off between weight, operational capacity, range and technological sophistication, adapting to different needs and underwater operation scenarios.

Figure 6: Comparative Table.

		ALTERNATIVES		
		GIRONA 500	LEOPARD	3300/1 MD
SAATY ANALYSIS MATRIX				
		IQUA	SAAB	TRITON
CRITERIA – PLATFORM	WEIGHT	200 Kg	1,200 Kg	2,100 Kg
CRITERIA – PLATFORM	MAX DEPTH	500 metros	1,000 metros	1,000 metros
CRITERIA – PLATFORM	PAYLOAD	35 Kg	205 Kg	200 Kg
CRITERIA – SYSTEMS	CONTROL / HMI	Remote controlled by RF	Remote controlled by cable: Joystick + Articulated Arm	1 Pilot Joystick + Touch Screen
CRITERIA – SYSTEMS	ELECTRONICS	Dual Frequency Sonar + Side Scan Sonar + Cam	Sonar + Multibeam Echosounder + Cams	Front sonar + Echosounder + Cam
CRITERIA – SYSTEMS	COMMS	Radio/WiFI/ Acoustic Modem	Cable	Underwater phone 10Khz (top)/ 27 Khz (bottom). Bi-directional acoustic modem
CRITERIA – PROPULSION	THRUSTERS	4 Pods	4 Pods	4 x 2Kw Pods
CRITERIA – PROPULSION	BATTERY & POWER SUPPLY	Lithium 2,9 kWh 6-8 Hours	3-Phase Umbilical Cable 380 V	Lithium 11 kWh 12 Hours
CRITERIA – PROPULSION	SPEED	2 Knots	4 Knots	3 Knots

Source: Authors.

Once the criteria and sub-criteria had been evaluated, pairwise comparisons were made, crossing the three systems, always one by one, choosing, according to the method, five values: "1", when they have the same preference or value; "3", when one is slightly higher; "5", slightly higher; "7", much higher; and "9", extremely higher. The comparisons would be made in 3x3 matrix for each criterion, allowing the calculation of the eigenvectors that will determine the relative priorities between the alternatives, as we can see in the Figure 7.

Figure 7: Main criteria and sub-criteria tables.

CRITERIA

	PLATFORM	SYSTEMS	PROPULSION
PLATFORM	1	1/3	1/7
SYSTEMS	3	1	1/3
PROPULSION	7	3	1

Value	Comment
1	A y B have the same importance
3	A is slightly more important than B
5	A is more important than B
7	A is much more important than B
9	A is extremely more important than B
1/3	A is slightly less important than B
1/5	A is less important than B
1/7	A is much less important than B
1/9	A is extremely less important than B

PLATFORM

	WEIGHT	MAX DEPTH	PAYLOAD
WEIGHT	1	1/9	1/3
MAX DEPTH	9	1	7
PAYLOAD	3	1/7	1

SYSTEMS

	CONTROL / HMI	ELECTRONICS	COMMS
CONTROL / HMI	1	5	9
ELECTRONICS	1/5	1	3
COMMS	1/9	1/3	1

PROPULSION

	THRUSTERS	BATTERY & POWER SUPPLY	SPEED
THRUSTERS	1	5	9
BATTERY & POWER SUPPLY	1/5	1	3
SPEED	1/9	1/3	1

Source: Authors.

4. Results and Discussion.

A search in the academic database "Dimensions " for patents and studies related to SUMERSIBLE, ROV and AUV yields an increasing number of citations, articles and number of authors.[5] The Figure 8 graph shows a trend that deserves deep analysis, especially considering the impact these technological advances have across various fields, from maritime exploration to naval security (Boretti, 2024)

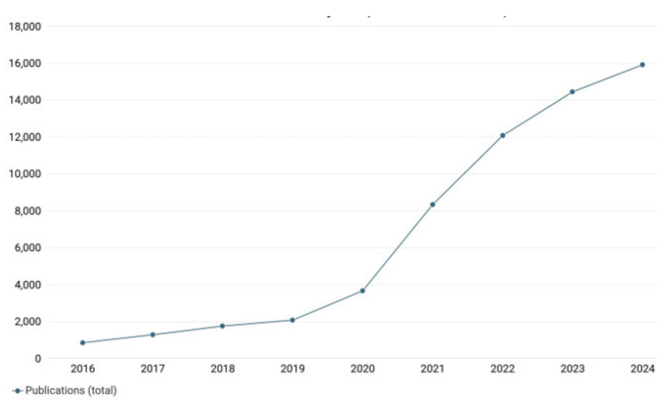
A detailed analysis shows a steady growth in the number of publications, but the left side of the graph reflects a time when unmanned submarine technology was in an early development stage, where researchers and developers were primarily focused on establishing the fundamental bases of these systems. The period at the right of the graph, shows exponential growth, with a particularly pronounced increase that reflects not only greater academic and commercial interest in unmanned submarine technology but also significant diversification in its applications, and coincides with several converging factors that have driven interest in these technologies. Also, the maturation of complementary technologies such as artificial intelligence / deep learning (Aubard et al., 2024), autonomous navi-

[5] Dimensions is a multidisciplinary database that collects information on scientific articles, patents, research funding, among other aspects. It provides access to a wide range of disciplines and allows advanced searches, impact metrics, and analysis of research trends.

gation systems, and improvements in underwater communications have opened new possibilities for ROV and AUV applications.

The final results obtained in the comparison of alternatives are quite enlightening, as we can see in Figure 9, as to which is the best naval vehicle to perform submarine salvage and rescue tasks. In our analysis, in order to weight the main criteria evaluation obtained from the tables of the Figure 10, the highest weight is obtained by propulsion; with a weight of 67%, it includes sub-criteria such as the type of propellers for steering, battery and autonomy, and speed. Of the three, the thrusters are the most important, with 75%.

Figure 8: Citations between 2016 and 2024.



Source: Dimension.

Figure 9: Final Results.

CRITERIA & SUBCRITERIA	WEIGHT RATIO	AUV GIRONA 500	ROV LEOPARD	DSV TRITON
PLATFORM	0,09	0,1	0,41	0,49
WEIGHT	0,07	0,67	0,06	0,27
DEPTH	0,78	0,05	0,47	0,47
PAYLOAD	0,15	0,06	0,27	0,67
SYSTEMS	0,24	0,06	0,23	0,71
CONTROL / HMI	0,75	0,06	0,19	0,75
ELECTRONICS	0,18	0,06	0,22	0,72
COMMS	0,07	0,06	0,65	0,29
PROPULSION	0,67	0,06	0,32	0,62
THRUSTERS	0,75	0,06	0,29	0,85
BATTERY & POWER SUPPLY	0,18	0,07	0,28	0,64
SPEED	0,07	0,07	0,64	0,28
		0,06	0,3	0,63

Source: Authors.

In the analysis of the naval platform criterion, the sub - criterion that has obtained more importance has been the maximum depth, with 78% more than the displacement of the vehicle, or the payload it can carry. We are looking for a system that can locate a sunken submarine or DISSUB, even below the collapse level, which is usually double the maximum operational level; let us think that the integrity of the hull may have been maintained thanks to demanding engineering calculations and, therefore, we need a naval platform that reaches about 1,000 meters (Conte de los Ríos, 2018). Finally, within the criterion referring to management systems, the most important sub-criterion is the control or HMI (Human-Machine Interface), which is fundamental for vehicle management. This criterion reached 75%, followed by electronic, acoustic and navigation systems with 18%, also vital for finding a DISSUB.

Figure 10: Criteria Evaluation.

CRITERIA

	PLATFORM	SYSTEMS	PROPULSION	WEIGHT
PLATFORM	1	1/3	1/7	0.09
SYSTEMS	3	1	1/3	0.24
PROPULSION	7	3	1	0.67

R.I. 0.0061

PLATFORM

	WEIGHT	MAX DEPTH	PAYLOAD	WEIGHT
WEIGHT	1	1/9	1/3	0.07
MAX DEPTH	9	1	7	0.78
PAYLOAD	3	1/7	1	0.15

R.I. 0.0708

SYSTEMS

	CONTROL / HMI	ELECTRONICS	COMMS	WEIGHT
CONTROL / HMI	1	5	9	0.75
ELECTRONICS	1/5	1	3	0.18
COMMS	1/9	1/3	1	0.07

R.I. 0.0252

PROPULSION

	THRUSTERS	BATTERY & POWER SUPPLY	SPEED	WEIGHT
THRUSTERS	1	5	9	0.75
BATTERY & POWER SUPPLY	1/5	1	3	0.18
SPEED	1/9	1/3	1	0.07

R.I. 0.0252

Source: Authors.

In the analysis of the three options: UAV, ROV and DSV by criteria, according to the AHP comparative matrixes that can be seen in figure 11, starting with propulsion which has a weight of 67%, we see that the DSV is preferred by 62%, compared to 32% for the ROV. Undoubtedly, larger thrusters to move a vehicle of larger displacement gives them both a certain advantage over the AUV. In the naval platform criterion, we also see that the ROV and the DSV are preferred by our experts, with a similar weight of 41% and 49% respectively, as they are systems that exceed the collapse depth and have a similar payload. Under the control system criterion, the ROV and the DSV are again the two most valued choices. In the case of the DSV, having the human piloting it as a sensor makes it ideal for the search tasks of a DISSUB and therefore reaches 71%.

In summary, although the AUV is a booming system with many possibilities, especially when it comes to risky or repetitive tasks, the human being is still the preferred system for tasks that require quick decisions and the evaluation of unexpected scenarios.

The advantage of the DSV; much more robust, both for its maneuvering capacity and stability, supported by the direct vision of the operator, and its autonomy without the need for cables that tie it to the surface, with respect to the ROV, makes it reach 63% of preference, compared to 30% of the ROV or 6% of the AUV. DSVs are currently the ideal instrument for deep sea exploration without the limits imposed by the reel and cable infrastructure of ROVs, being perfectly safe and certified by the

Figure 11: Platforms evaluation.

WEIGHT

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRNOA	1	9	3	0,67
LEOPARD	1/9	1	1/5	0,06
TRITON	1/3	5	1	0,27

R.I. 0,0252

MAX DEPTH

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRNOA	1	1/9	1/9	0,05
LEOPARD	9	1	1	0,47
TRITON	9	1	1	0,47

R.I. 0,0000

PAYLOAD

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRNOA	1	1/5	1/9	0,06
LEOPARD	5	1	1/3	0,27
TRITON	9	3	1	0,67

R.I. 0,0252

THRUSTERS

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/7	1/9	0,06
LEOPARD	7	1	1/3	0,29
TRITON	9	3	1	0,65

R.I. 0,0701

SPEED

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/7	1/5	0,07
LEOPARD	7	1	3	0,64
TRITON	5	1/3	1	0,28

R.I. 0,0565

CONTROL/HMI

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/5	1/9	0,06
LEOPARD	5	1	1/7	0,19
TRITON	9	7	1	0,75

R.I. 0,1889

ELECTRONICS

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/5	1/9	0,06
LEOPARD	5	1	1/5	0,22
TRITON	9	5	1	0,72

R.I. 0,1035

COMMS

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/9	1/7	0,06
LEOPARD	9	1	3	0,65
TRITON	7	1/3	1	0,29

R.I. 0,0701

BATTERY & POWER SUPPLY

	GIRONA	LEOPARD	TRITON	WEIGHT
GIRONA	1	1/5	1/7	0,07
LEOPARD	5	1	1/3	0,28
TRITON	7	3	1	0,64

R.I. 0,0565

Source: Authors.

various classification societies (Chen *et al.*, 2022).

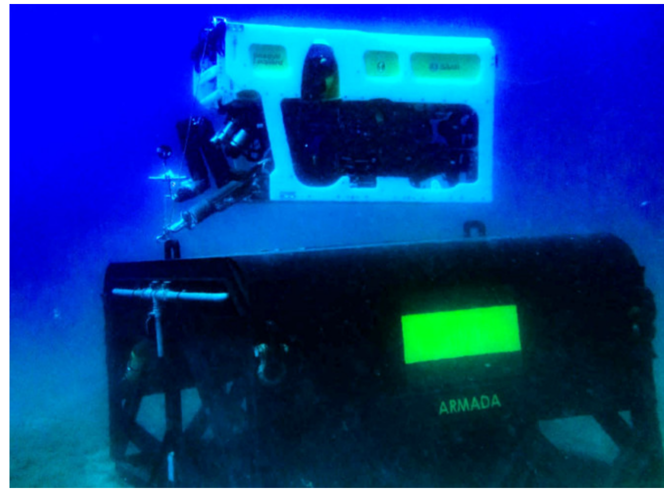
This methodology has an indicator that controls the degree of consistency of the scores we make in each phase of the process, by establishing the relative importance between the elements of each level. This indicator, is used to control the subjectivity, coherence and consistency of our experts. In general, values higher than 10 per 100 indicate inconsistency; in our case, all of them were below 7 per 100, which is a good figure. Finally, this multicriteria technique has been widely studied and is used in many Defense procurement programs, being perhaps the choice of the Pilatus PC-21 aircraft, for instruction of the General Air Academy of Professor Sanchez-Lozano, the best known (Sánchez-Lozano, Correa-Rubio and Fernández-Martínez, 2022).

Conclusions.

The need for an underwater rescue system becomes critical with the arrival of the S-80 submarine and the future incorporation of the new underwater intervention vessels (BAM-IS) with advanced capabilities in submarine rescue and salvage. Recent accidents such as the ”Villa de Pitanxo” (Marqués *et al.*, 2024) or the crash of the Spanish Air Force Superpuma, on October 22, 2015, off the coast of Western Sahara, make it necessary to consider the need for this capability within the Navy.

All the nations with naval projection interests are working in programs for this kind of vehicles, in order to increase its capability in this field, with research projects in a cooperative technology route. The related typical application cases to analyze the current technical maturity involve lot of aspects: Control architecture for navigation (Lastra *et al.*, 2016), he development of technologies in the fields of human-computer interaction control technology, intelligent decision-making technology, communication anti-jamming technology, and open hardware and software technology (Li *et al.*, 2024).

Figure 12: ROV Leopard in operation.



Source: Spanish Navy.

Today, we find ourselves in an increasingly complex world, where the interconnection between different aspects of systems and technology are growing. Faced with this growing complexity, since the 1970s, numerous methodologies based on the consideration of numerous criteria have begun to spread, one of the best known of which is the Multi-Criteria Methodology as a Human Decision Support System.

Figure 13: DSV Triton Operating from the Spanish Navy Submarine Rescue Ship ”Neptuno”.

Source: Spanish Navy.

The final result of the selection carried out by our experts has been the DSV Triton (Figure 13), followed closely by the ROV Leopard (Figure 12), thanks mainly to its maximum height and being very well balanced in the rest of the factors, something that fits very well with our needs. Most importantly, the submersibles have one operator, the best possible sensor and no cable to tie them to the mother ship and limit their navigational movement. DSVs are high-performance, incredibly reliable deep diving vehicles that offer 360-degree, immersive views with unparalleled search capability (Pan and Cui, 2020).

The custom-designed research, exploration and salvage package makes them unique, and they provide unparalleled access to one of the planet's last unexplored frontiers, the uncharted deep sea, which opens up exploration of important marine genetic resources.

Acknowledgements.

We would like to thank the Commander of the Spanish Navy Undersea Search and Rescue Vessel "Neptuno" for the information provided to carry out this study, as well as his help in determining the most important criteria for a system to be used at great depths. We would also like to thank Colonel Carlos Luis Ruiz López for his help with AHP.

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