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Launching systems for unmanned vehicles onboard naval vessels

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***Abstract*— Unmanned vehicles can replace humans in humanitarian and military operations, requiring ships to have innovative capabilities for launching and recovering them. However, the variety of unmanned vehicles makes it difficult to create standardized interfaces, and their development often outpaces the lifespan of ships. Integrating unmanned vehicles on naval vessels is complex due to technical requirements and limited space. Engineers must consider cost efficiency, flexibility, and operational impact. This paper presents technologies and solutions for launching unmanned aerial vehicles (UAVs) from front-line ships, with their pros and cons. To this end, Fuzzy Analytic Hierarchy Process (FAHP) has been here employed to rank the main options. Among them, the electromagnetic catapult is the most promising option for launching UAVs from front-line naval ships and it is worthy of further development. Besides, despite having limited capacity, bungee cords can be used until the technology of the electromagnetic catapult is tested and ready to take the place of the former.**

***Index Terms*— Electromagnetic Launch System, Fuzzy Analytic Hierarchy Process, Launching systems, Naval vessels, Unmanned Aerial Vehicle.**

I. INTRODUCTION

The recent conflicts, the globalization of the economy and the proliferation of illicit maritime traffic give the sea an increasingly geostrategic centrality. [1] The depicted scenario highlights the crucial role of the sea in our overall prosperity, safety, and well-being, underscoring the significant responsibility of the Navy as the primary custodian of our collective marine domain.

Therefore, the need emerges to provide the Navy with a fleet composed of ships with outstanding versatility and operational flexibility. [2] The fleet should be structured into naval groups centered on ships with advanced aerial capabilities geared towards marine control in all three dimensions (i.e., aerospace, surface, and underwater), a robust submarine component comprising both manned and unmanned vehicles capable of seabed surveillance, and a highly mobile and autonomous amphibious force with superior logistical capabilities [3,4,5]. At the same time, with the advancement in technology, unmanned vehicles have become more efficient and more popular than ever. Advanced programming, better components, sensors with high precision, and a better understanding of technology are leading to unmanned vehicles not only remotely operated but also autonomous. Nowadays, when a task is too dangerous, inconvenient, or straight out impossible for humans to perform (e.g., hazardous environment, or inaccessible place) unmanned vehicles can carry it out [6].

Focusing on front-line naval vessels (e.g. destroyers, frigates), the use of unmanned vehicles has increased in the last decade. Warships are becoming even more multi-purpose platforms able to carry out a big variety of missions in a wide range of scenarios [7,8]. Unmanned vehicles present numerous advantages, including the ability to augment a ship's situational awareness, while simultaneously promoting crew safety by enabling them to maintain a safe distance during hazardous missions [9]. Moreover, the possibility to operate multiple unmanned vehicles from the same vessel would significantly enhance its capacity for both surveillance and strike capabilities. Due to the high demand for such vehicles, numerous types have been developed with strong differences in both layout and function. Thus, appropriate systems for launching and handling are required too.

Unmanned vehicles used on naval vessels are divided into three categories: Unmanned Aerial Vehicle (UAV), Unmanned Surface Vehicle (USV), and Unmanned Underwater Vehicle (UUV). UAVs are widely regarded as an effective force multiplier due to their numerous advantages. These benefits are often achieved at a reduced risk and cost in comparison to employing an equivalent manned aircraft for the same task [10]. Typical uses for the navy include:

- Shadowing enemy fleets;
- Decoying missiles by the emission of artificial signatures;
- Electronic intelligence;
- Relaying radio signals;
- Anti-submarine warfare (e.g. Placement and monitoring of sonar buoys);
- Optical surveillance and reconnaissance.

Many criteria can be used for UAV classification: i.e., weight, maximum altitude, operational range, and flight time capability. NATO provided a simplified classification method taking into account the maximum operating height and weight/volume of the vehicle [11]. There are also more comprehensive and complex classifications, but these are too detailed to be relevant to this study.

A key factor is how the UAVs take off and land from a naval platform. They are generally divided into Conventional Take-Off and Landing (CTOL) and Vertical Take-Off and Landing (VTOL) systems. For naval purposes, there is often a limitation on the available runway, especially for frigates and other smaller ships, hence the so-called Point Take-Off and Landing (PTOL) UAVs are being developed. In between these two categories, there are Short Take-Off and Landing (STOL) vehicles. These categories are in many cases connected to the type of aircraft. Fixed-wing UAVs normally fall under CTOL, STOL, or PTOL categories while rotorcraft or tilt-rotor UAVs fall under the VTOL category [12].

In this paper, we will focus on types 1 and 2 (NATO classification), i.e. unmanned fixed-wing launching systems from front-line vessels without a continuous flight deck. We will proceed with an overview of the launching systems employed today. A multi-criteria analysis to determine which is the best solution will be conducted according to the rules of the Fuzzy Analytical Hierarchy Process (FAHP) [13].

The objective of this paper is to investigate the influence of UAV launching systems on naval ship design [14,15] and to formulate potential solutions that could be implementedshortly soon . This will entail analyzing the critical factors associated with fitting UAVs onto naval vessels, identifying current and prospective approaches for launching these vehicles, and outlining their respective advantages and limitations. This assessment will provide a basis for initiating the design process at an early stage.

II. Technology Review

Conventionally, fixed-wing UAVs use a runway to accelerate up to the required take-off speed. The necessary thrust is provided by the own vehicle propulsion and therefore there is no need to take special measures. For fixed-wing UAVs used onboard front-line vessels, the situation is more complex. On such vessels space is limited and it is not possible to allocate onboard runway allowing the AUV to reach the necessary take-off speed. Alternative methods for making take-off possible must therefore be considered. Different technologies can be used to provide the necessary thrust despite the limited space available onboard. To this end, the most common technologies currently adopted are rocket-assisted take-off, bungee cords, hydraulic launchers, and pneumatic launchers. Besides, another emerging technology is worthy of investigation: the electromagnetic catapult.

A. Rocket Assisted Take-Off

Rocket Assisted Take-Off (RATO) is a type of assisted take-off for helping aerial vehicles into the air by providing additional thrust in the form of small rockets [16]. The UAV is placed on an inclined support and a rechargeable propulsion system is connected to the aircraft fuselage through dedicated arrangements. In the take-off phase, the rocket (launch charge) is ignited and this provides the necessary thrust for take-off. Once its function is exhausted, the rocket is released by the system which is now able to move and keep flying thanks to its standard propulsion. In this manner, the rocket does not add weight to the UAV during the subsequent phases of the mission. When the rocket is released, it falls into the sea, which is not positive for the environment. The sizes and weights of the components required by the RATO are small and therefore this launching system can be easily integrated into a front-line naval vessel. At the same time, attention must be paid to the type of material used. Rockets are explosive, thus their handling should be carried out with care, making sure that RATO operations do not interfere with other onboard activities. Furthermore, special precautions must be taken for launch charges stowage. Temperatures must be continuously monitored in the room and a dedicated fire protection system must be fitted to prevent serious consequences in the event of an accident. Another concern is the presence of an open flame on the flight deck during the launch process. Firstly, the flame and thrust generated by the rocket could damage the flight deck if it is made of sensitive materials (e.g., composite material). Secondly, the flames, heat, and smoke generated by the rocket could affect the ship's stealthiness. The RATO system offers numerous advantages, including the elimination of the necessity for specialized infrastructure and the utilization of a minimal amount of space. Fig. 1 shows an example of Rocked Assisted Take-Off launcher.

Figure 1 RATO launching a UAV (source: https://www.globalsecurity.org/intell/systems)

B. Bungee Cord

This system uses energy stored in highly elastic bungee cords to launch UAVs. The arrangement is completed by a metal rail, tilted with a proper angle to provide the best aerodynamic conditions and higher lift to the launched UAV, and by a winch that tensions the elastic bungee cord (or elastic bungee cords) before every launch [17]. This system is therefore very simple and light, it has a very low impact on the operation of the ship and it is easily integrated onboard naval vessels. [18] The only additional provision is to have an electric motor able to tighten elastic bungee cords before each launch. Apart from this component, this system does not employ any modern electrical components and it is extremely quiet and stealthy. However, this technology is not widely applicable. The carrying capacity is rather low and therefore only smaller unmanned aircraft vehicles can utilize this system for take-off. Moreover, owing to the low energy density stored in the elastic cords, a considerably lengthy metal rail would be necessary, in contrast to other methods. This could result in difficulties concerning the storage and preparation of the system on the flight deck in the event of its usage. Finally, the initial acceleration of the UAV is very high. Fig. 2 shows an example of a bungee cord launcher.

Figure 2 UAV take-off from a bungee cord launcher from navy.mil

C. Hydraulic launcher

The hydraulic launcher is a system that uses oil pressure to provide the required thrust for the UAVs' take-off [19]. An essential element for the operation of this system is a two-compartment cylinder. The two compartments are separated by a piston that has on one side a compressible gas and on the other side hydraulic oil pressurized by a volumetric pump driven by an electric motor. To accumulate the energy needed for the launch, the oil is pumped at high pressure into the hydraulic cylinder and as a result, the gas is compressed inside its chamber. The side of the oil-containing cylinder is connected through a distributor drawer and fast-opening valves to a hydraulic motor. This, in turn, is connected to a winch that sets in motion the cradle on which the UAV to launch is placed. To launch the UAV, the distributor drawer is moved and the valves are opened. In this way, the gas in the cylinder expands and the resulting oil flow drives the hydraulic motor, which accelerates the cradle and consequently the UAV. This system is certainly more complex than the previous ones and requires preparations and power sources to function. Nevertheless, it has numerous advantages. It allows reaching high launch speeds and initial light acceleration to avoid stressing the unmanned vehicle material and sensors. Fig. 3 shows an example of hydraulic catapult.

Figure 3 Hydraulic catapult launching a UAV (source: malaysiandefence.com)

D. Pneumatic launcher

Pneumatic launchers are very similar to hydraulic ones. In this case, the energy needed for the launch is accumulated through a compressed gas (usually air). The launch is done by leaking the air accumulated in a cylinder through a valve and then operating the cradle that drags the unmanned aerial vehicle. By changing the air pressure, it is possible to modulate the thrust depending on the weight and speed required by the individual aircraft. The negative aspects of this system are that it is necessary to provide a compressor to refill the cylinders near the flight deck and that it takes time to refill the cylinders. Fig. 4 shows an example of a pneumatic launcher.

Figure 4 Scaneagle UAV launch by a pneumatic catapult (source: navy.gov.au)

E. Electromagnetic launching system

The electromagnetic launching system utilizes a Linear Induction Motor (LIM) to accelerate UAV [20,21]. This system can be described as a traditional electric motor developed on a plane to enable the take-off of an aerial vehicle. The stator powered by electric current produces a magnetic field that sets in motion what in the rotary electric motor is the rotor, in this case, defined as a slide. The system is completed by a series of arrangements for its own integration and correct functioning. An Uninterruptible Power Station (UPS) is dedicated to the system to store the energy needed for the launch and avoid a voltage drop in the onboard grid. Thanks to advances in technology, it is now possible to modulate the thrust and acceleration of the UAV by acting on the voltage and current values provided to the stator. To reduce losses and increase efficiency, this system provides a feedback control that feeds only the windings involved in the acceleration of the UAV. The main advantages of such a system are the possibility of being used for the launch of different UAVs (different in weight and size) and modulating their launching speed/force. Moreover, such a system turns out easily integrable on future naval vessels which are previewed to be full-electric. [22,23] The downside of such a system is certainly the cost. However, as this technology will become more and more widespread, it will result in lower acquisition costs.

III. METHODOLOGY

A. Multi-criteria decision process

In order to determine which of the proposed systems is the best solution to be implemented on a front-line naval ship for the launch of small unmanned aircraft, it became necessary to use decision support tools. Making a multi-criteria selection between various categories or criteria that cannot be measured using the same scale can be challenging. Several mathematical theories have been developed for this purpose, e.g. AHP (Analytical Hierarchy Process), ELECTRE, PROMETHEE, and others. Among these theories, in this paper, the Fuzzy Analytic Hierarchy Process (FAHP) has been applied. The FAHP technique is widely used in the maritime industry field to support Multiple Criteria Decision Making (MCDM) processes related to economic, technical, safety, and design issues [24,25,26].

In AHP [13], the problem is decomposed into a hierarchic set of sub-problems subject to the experts' judgment employing pairwise comparison. The relative importance of each couple of criteria or attributes is assigned using a linguistic scale. Among MCDC techniques, it provides the methodology to convert those simple comparisons into varying degrees of relevance. However, since the opinions are by definition imprecise and vague, the fuzzy set theory has been applied to develop the so-called FAHP [27]. It is common practice [28,29] to convert each preference into a triangular fuzzy number $\mathbf{t} = (t^l, t^m, t^u)$ using a linguistic scale (Tab. I). Each expert compares all the couples of criteria via linguistic preferences. Then, all the results are converted into the pairwise comparison matrix containing associated fuzzy numbers:

$$\mathbf{D}^k = \begin{bmatrix} \mathbf{d}_{11}^k & \cdots & \mathbf{d}_{1n}^k \\ \vdots & \ddots & \vdots \\ \mathbf{d}_{n1}^k & \cdots & \mathbf{d}_{1n}^k \end{bmatrix} \quad (1)$$

where $\mathbf{d}^k_{ij}$ is the k-th expert's preference related to the i-th criterion over the j-th criterion.

To achieve rational results all pairwise matrixes' consistency is checked through the consistency index NI, which shall not be greater than 0.1 [30].

TABLE I. Adopted linguistic scale

	Preference	1st criteria fuzzy number	2nd criteria fuzzy number
1st criteria	Extreme	(9,9,9)	(1/9,1/9,1/9)
	Strong	(6,7,8)	(1/8,1/7,1/6)
	Fair	(4,5,6)	(1/6,1/5,1/4)
	Moderate	(2,3,4)	(1/4,1/3,1/2)
vs	Equal	(1,1,1)	(1,1,1)
2nd criteria	Moderate	(1/4,1/3,1/2)	(2,3,4)
	Fair	(1/6,1/5,1/4)	(4,5,6)
	Strong	(1/8,1/7,1/6)	(6,7,8)
	Extreme	(1/9,1/9,1/9)	(9,9,9)

In this paper, the authors' preferences are taken into account. To correctly evaluate the group fuzzy preferences several methods have been considered. Among the others, the geometric mean has been applied, since it is one of the higher-quality synthesis techniques according to [31]:

$$\mathbf{d}_{ij} = \left(\prod_{k=1}^{K} \mathbf{d}_{ij}^k \right)^{1/K} \quad (2)$$

Based on averaged preferences, the fuzzy pairwise comparison matrix is updated obtaining the average pairwise comparison matrix **D**. Then, the fuzzy weight $\mathbf{w}_i$ of each criterion is calculated as the normalized geometric mean of all the items from the corresponding row of the average matrix [32]:

$$\mathbf{w}_{ij} = \left(\prod_{j=1}^{n} \mathbf{d}_{ij} \right)^{1/n} \otimes \left[\sum_{i=1}^{n} \left(\prod_{j=1}^{n} \mathbf{d}_{ij} \right)^{1/n} \right]^{-1} \quad (3)$$

Since such weights are still triangular fuzzy numbers, they are "defuzzified" obtaining a mean weight for each criterion evaluated with the center of area method as:

$$\overline{w}_i = \frac{w_i^l + w_i^m + w_i^u}{3} \quad (4)$$

Eventually, the mean weights are normalized to obtain the final weight for each criterion:

$$w_i = \overline{w}_i \left(\sum_{i=1}^{n} \overline{w}_i \right)^{-1} \quad (5)$$

When using FAHP the first pairwise comparisons are between criteria. In the next step, solutions are pairwise compared in the different criteria and the same problem can be solved. This results in a vector containing each option's importance in that criterium. By multiplying the vector with the related criteria importance, the option's local importance in that category is computed. This is performed for every category. Given a solution, its global importance is obtained by summing all its local importances. Solutions' global importance can be compared with each other to determine a ranking.

B. Evaluation analysis criteria

Concerning the problem addressed in this paper, the relevant design criteria have been identified. They are:

- **Impact on ship design.** To what extent the launching system impacts the ship's design is evaluated, taking into account how the system is demanding in terms of ship resources (e.g. electric power, compressed air, etc.) or infrastructures (e.g. flight deck materials).
- **Safety issues**. Risks of damaging the ship, the UAV, or harming crew during launch operations.
- **Impact on ship operations.** To what extent the launching system affects the ship's normal operational effectiveness.
- **Weight.** The weight of the launch system.
- **Deck footprint.** The deck area required by the launching system in both stowed and deployed mode.
- **Cost.** Estimations on the purchase cost considering whether parts and/or subsystems are commercially available or not.

- **Setup time.** The time required to set up the launching system and prepare it for operation.
- **Manning.** The number of crew members required to operate the launching system.

All of the criteria are of the benefit type, meaning that the higher the value assigned to a technical solution, the better the solution's performance is rated.

C. *Design Criteria weights assessment*

According to the methodology provided in Section III.A, the weights of the design criteria have been evaluated and are provided in Fig. 5.

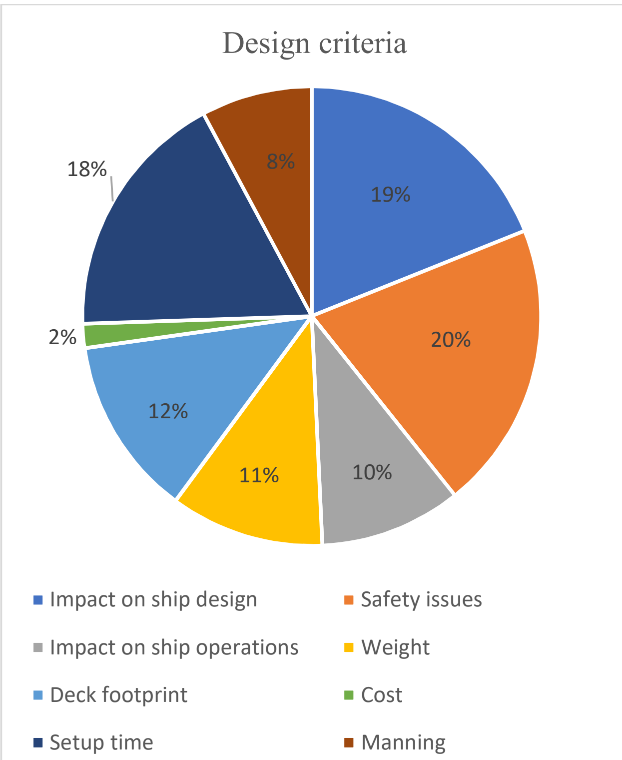

Figure 5 Normalised weights of design criteria

IV. CASE STUDY: TECHNOLOGIES RANKING

Individual pair-wise comparisons are not listed in the following section. For reasons of space, it was preferred to present and discuss different launch systems' pros and cons for each design criterion. The maximum value of the consistency index obtained was 0.083.

A. *Impact on ship design*

Hydraulic and pneumatic catapult systems have the greatest impact on ship design (lowest benefit) due to their size. They require to be connected to the onboard power supply or compressed air/oil circuit. Moreover, they demand further subsystems (e.g., cylinders of storage compressed air and hydraulic unit) that together can require a total volume comparable to that of a one-TEU container. Certainly, the solution with bungee cords brings some minor relapses in the ship design compared to the two previously analyzed systems. However, due to the low power density of this system, it may be necessary to have an excessive length in the support for the launch such as to make it difficult to integrate on the flight deck of a front-line ship. Using the RATO system may seem to be the least invasive system for onboard integration. But considering the system as a whole, the repercussions are considerable. Firstly, the area of the flight deck affected by the rocket exhaust must be specially designed and protected. In addition, the rockets are flammable and explosive, they must therefore be stowed in dedicated rooms and also the handling must take place with dedicated systems. Finally, the electromagnetic system has a low relapse on ship design. More and more full-electric ships offer all the necessary predispositions for the electric power supply [33,34]. Moreover, electronic components are more and more small and lightweight. Consequently, the requirements of the system for feeding and control are minimal. Possessing a high-power density, the launch system would have a minimal footprint resulting in a very low impact on ship design. Based on these considerations and the application of the FAHP process, the results presented in Fig. 6 have been obtained.

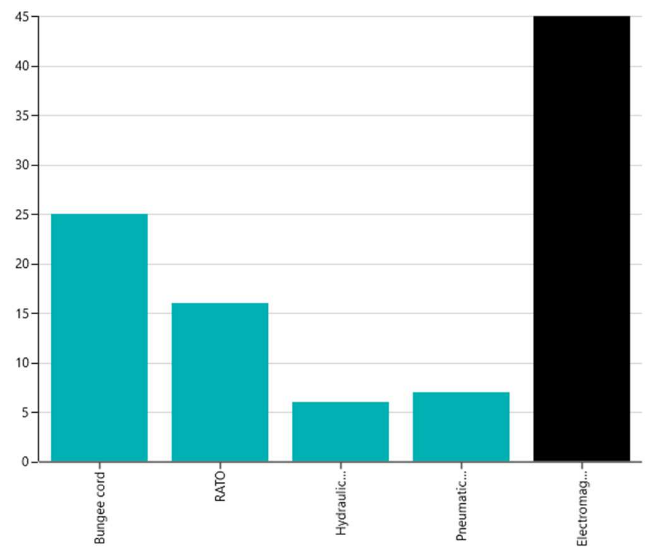

Figure 6 Benefits in terms of impact on ship design

B. *Safety issues*

Certainly, the RATO is the most hazardous launching system because of the flames and fumes produced by the rocket. Catapult solutions differ slightly due to different launch control systems. In the bungee cord system, there is no control system, so among the catapult launchers, this is certainly the least safe. Hydraulic and pneumatic launchers have control systems such as pressure gauges and safety valves, so they are quite safer. Lastly, the electromagnetic system includes a feedback mechanism that monitors the launch state through specialized sensors in real-time, enabling personnel to take necessary measures for ensuring the launch's safety and success. Among the systems analyzed in this review, it is considered the safest. Based on these considerations and the application of the FAHP process, the results presented in Fig. 7 have been obtained.

C. *Impact on ship operations*

The impact on the ship operations is mainly related to the need for relative wind for take-off required by individual systems.

Such necessity is greater in the case of the RATO launching system since, in the phase of transition from the charge booster to the auto-propulsion, the AUV is very unstable and, therefore, requires stable wind conditions. Moreover, in case of recovery of the booster charge, the ship has to maneuver with a strong drawback on all the other operations. Bungee cord launcher also requires good relative wind conditions to make safe launches. Based on these considerations and the application of the FAHP process, the results presented in Fig. 8 have been obtained.

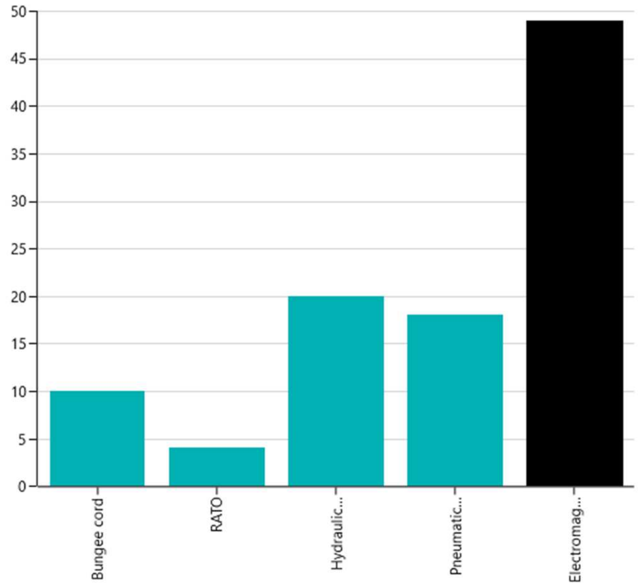

Figure 7 Benefits in terms of safety issues

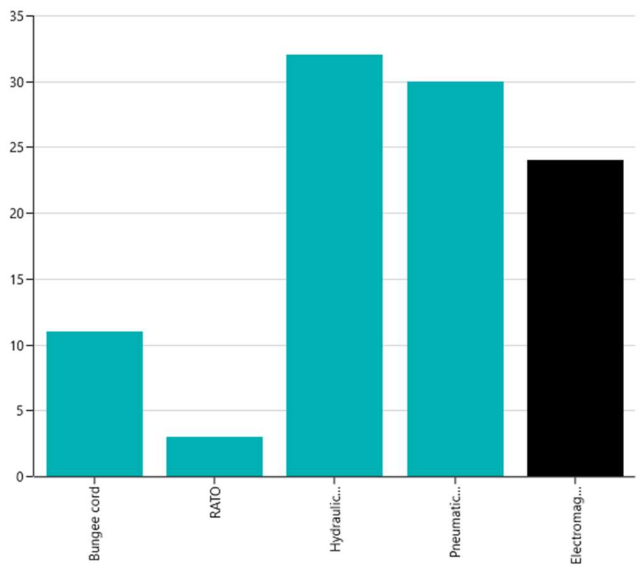

Figure 8 Benefits in terms of impact on ship operations

D. Weight

Concerning launching system weight, the system that might seem to present the best performances, at first sight, is the RATO. On the other hand, considering a charge is needed for every launching operation the weight becomes relevant if multiple AUV missions shall be granted, especially for non-reusable rockets. The catapult systems are disadvantageous because of the weight of the structure needed to perform the launch. Among the catapult systems those that have greater weight are certainly the hydraulic and pneumatic launchers because we must also consider the auxiliary systems that allow their operation (e.g., air tank and hydraulic control unit). Bungee cord systems perform well but have a limited capacity in terms of the weight of launched AUVs. Based on these considerations and the application of the FAHP process, the results presented in Fig. 9 have been obtained.

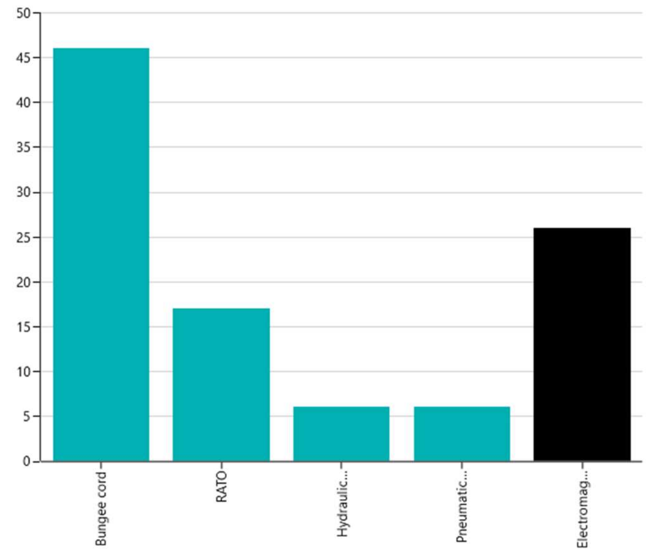

Figure 9 Benefits in terms of weight

E. Deck footprint

Both the hydraulic and pneumatic pitchers are unacttractive in this criterion. They take up considerable space also because of their auxiliaries. The electromagnetic and bungee cords systems, unlike the previous ones, are not as space-demanding due to limited required auxiliaries and, therefore, are more advantageous. The RATO system takes more space than it may seem. During the launch phase, the flight deck must be free from any delicate system/vehicle due to the flames and hot fumes produced by the rocket. Besides, a charges store is required onboard. Based on these considerations and the application of the FAHP process, the results presented in Fig. 10 have been obtained.

F. Cost

Hydraulic and pneumatic launchers require expensive machinery and auxiliaries. The costs of the electromagnetic catapult are even higher due to the required electronic components. The outlook for this system is characterized by a gradual reduction in costs that are associated with its progressively expanding use. As for the bungee cord and RATO systems, they are really simple installations in terms of technology and, consequently, they have lower purchase costs. However, in the case of the RATO, the manning costs are more relevant since launch charges shall be continuously purchased to grant its operation. Based on these considerations and the application of the FAHP process, the results presented in Fig. 11 have been obtained.

G. Setup time

Of all the options being considered, the pneumatic catapult has the longest deployment time and the longest interval required

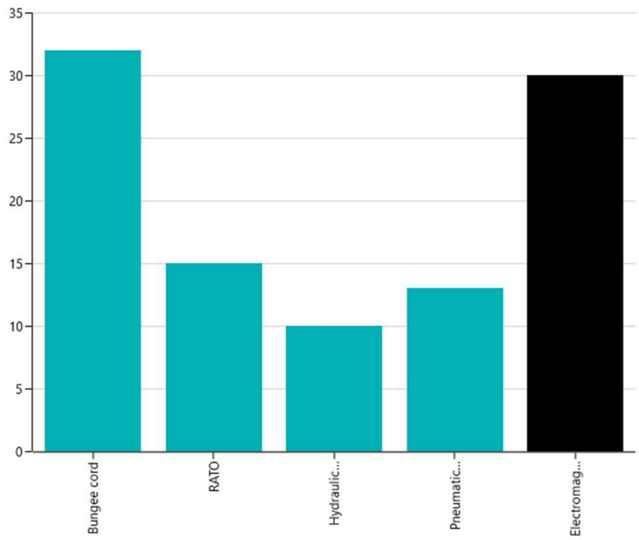

Figure 10 Benefits in terms of deck footprint

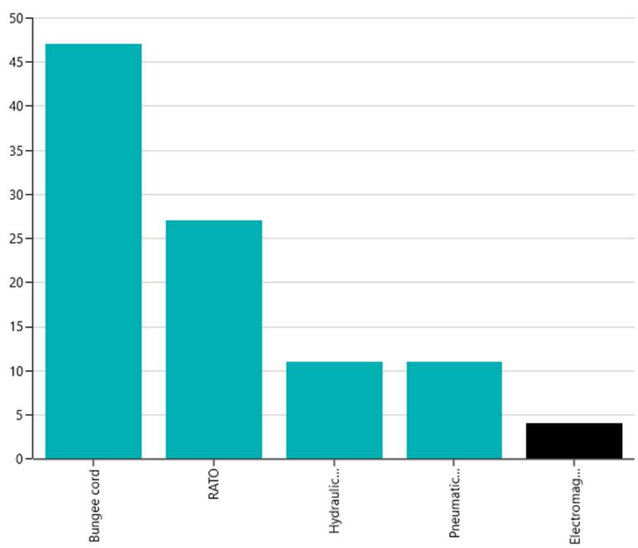

Figure 11 Benefits in terms of cost

between two launches. After each launch, the cylinder pressure of the pneumatic catapult must be refilled, and this process takes time due to the need for the compressor to operate. The hydraulic system is affected by similar issues, but a hydraulic motor can reach the operating pressure in less time. The bungee cord system requires time for rope retrieving, while the RATO takes time to connect the new launch charge to the UAV. From this point of view, the system that introduces the greatest efficiency is the electromagnetic catapult, which rapidly accumulates the power for consecutive AUV launches thanks to dedicated UPSs. Based on these considerations and the application of the FAHP process, the results presented in Fig. 12 have been obtained.

H. Manning

The bungee launcher is highly maneuverable and can be operated by as few as two individuals, facilitating its preparation and readiness for launch. This is also due to the

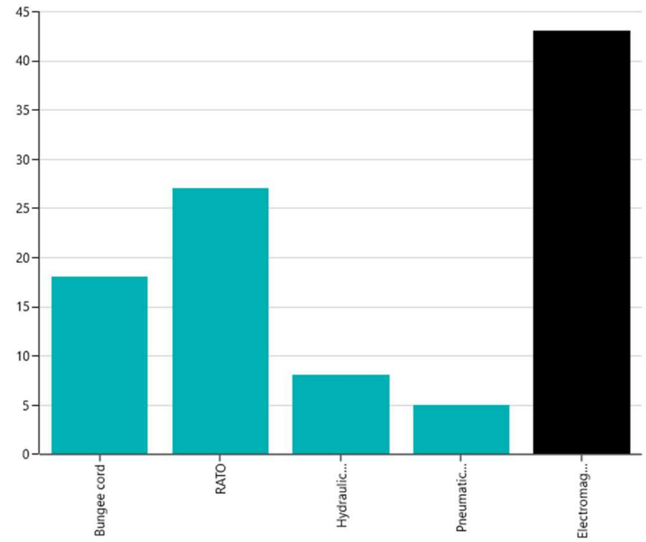

Figure 12 Benefits in terms of setup time

limited size of AUVs that can be launched. Hydraulic, pneumatic, and electromagnetic launchers require only one operator to run once positioned, but they require more people for deployment and to move larger UAVs. The RATO launcher requires only one person to be fired, but a dedicated stand-by fire squad is necessary to limit fire risk. Based on these considerations and the application of the FAHP process, the results presented in Fig. 13 have been obtained.

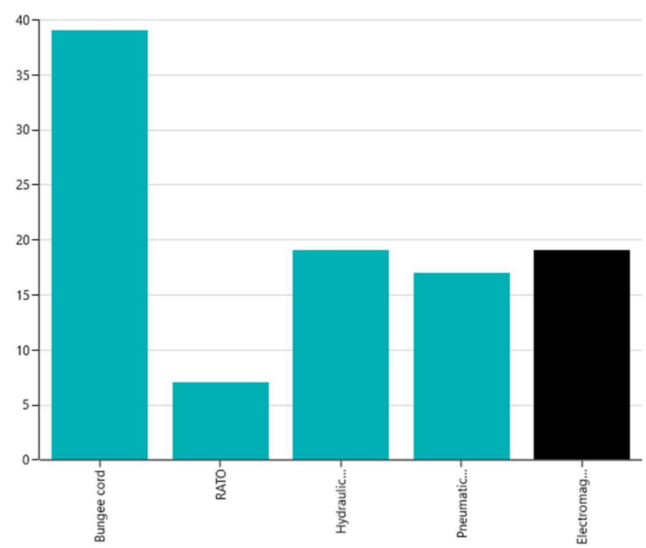

Figure 13 Benefits in terms of manning

I. Ranking

Fig. 14 displays the influence of each criterion on the overall assessment of every alternative. The local importance of each option in a given category is obtained by multiplying the vector of each benefit evaluation with the corresponding criteria importance (refer to Fig. 5). This process is repeated for all categories. The summation of all the local importances of an option yields its global importance. By comparing the global importance of different options, the most favorable solution can be identified. The final result of this comparison is illustrated in Fig. 15.

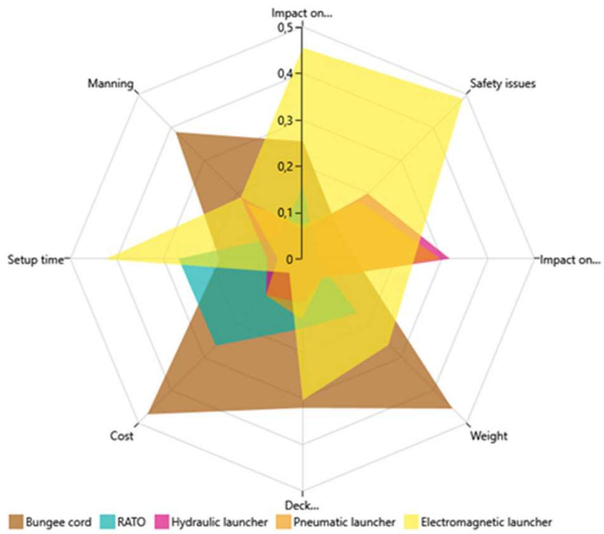

Figure 14 FAHP attributes results

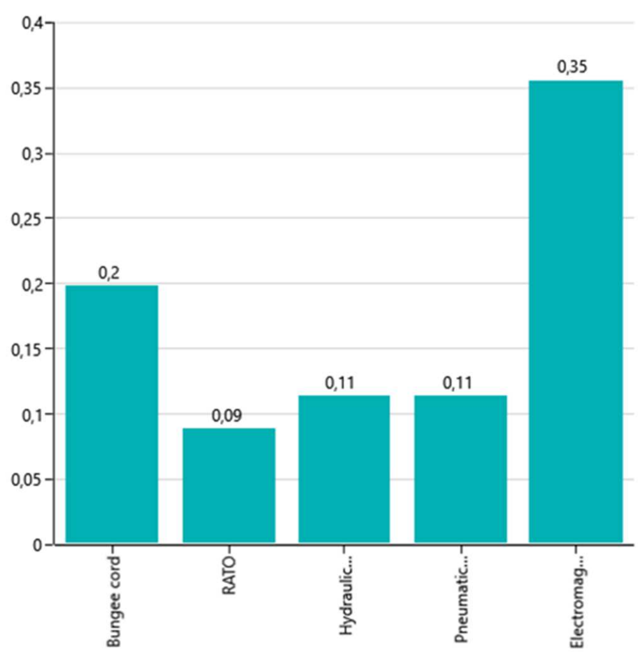

Figure 15 Ranking of the considered options

V. CONCLUSION

This study provides an overview of the current technology for launching small UAVs that can be utilized on front-line naval vessels. The use of LIM to generate the necessary thrust and speed for UAV takeoff is also explored. FAHP has been employed to rank the various options. The electromagnetic catapult is identified as the best solution for integrating small UAVs on front-line naval vessels. The primary criteria considered in the analysis were the impact on ship design and safety. Besides, it is recommended to discontinue the use of RATO and transitionally employ bungee cords for light UAVs, which have been ranked as the second option due to their simplicity and low cost. To face the increasing size of UAVs, investing in hydraulic or pneumatic launchers should be avoided, and only electromagnetic ones are advisable.

Nevertheless, electromagnetic technology is known to have a significant disadvantage: high cost. However, since the study is centered on naval vessels, cost plays a minor role compared to other factors and other maritime sectors. The defense sector has historically served as a testbed for new technologies and should continue to do so, while also encouraging industry research with public funding. This approach could facilitate the wider adoption of these technologies and lead to a subsequent reduction in their costs.

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