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Revolutionizing ocean engineering: the impact of autonomous vehicles

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Abstract

In ocean engineering, engineering principles are applied to the ocean domain. Advanced technology is facilitating efficient exploration of oceanic regions with minimal human intervention, and autonomous vehicles are increasingly used to automate various ocean engineering tasks. However, using fully autonomous vehicles raises ethical and legal concerns that must be properly regulated. Nowadays, the most common applications of autonomous vehicles in the ocean domain include infrastructure maintenance, underwater mapping, resource exploration, environmental monitoring, and various military operations such as mine warfare (MW) and intelligence, surveillance, and reconnaissance (ISR). This article explores the prevalent applications of autonomous vehicles in ocean engineering, analyzing existing regulations, liability and accountability issues, data privacy, cybersecurity challenges, and interoperability. Through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, it was possible to better understand the current state of using autonomous vehicles in ocean engineering and develop a possible future strategy in the field. To make the usage of autonomous vehicles more reliable in ocean engineering, it is essential to advance them technologically and update the existing laws that deal with these kinds of applications.

Keywords: *ocean engineering, autonomous vehicles, marine technology, robotics*

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1. Introduction

The ocean serves as a major source of natural resources such as food, sustainable energy, and drinking water, among others [1–3]. This makes ocean engineering [4], that is, the application of engineering principles into the ocean domain, an essential field of engineering. Because of its importance to humans, investments that are made on the applications in the ocean domain must be permanent. Advancements in technology play a major role in improving the efficiency and performance of the exploration tasks with reduced, or even without, human intervention [5, 6].

Autonomous vehicles are becoming increasingly popular worldwide, and their applications are becoming widespread [7]. However, the use of fully *autonomous* vehicles is still facing restrictions due to the rising ethical and legal concerns, which necessitates the proper regulation of policies in this field [8, 9]. One of the most discussed concerns is determining who bears the responsibility in the event of an accident, a concept commonly referred to as liability [10]. Improvements and updates are crucial in all fields, including legislation. Because of the new applications and developments emerging every day in the autonomous world, legislation must also be updated according to these advancements.

The most common tasks in ocean engineering include designing, constructing, and maintaining infrastructures [11]; underwater mapping [12], monitoring, and exploration [13]; identifying and exploring natural resources [1]; environmental monitoring and protection [14]; and developing sustainable energy sources [15]. Autonomous vehicles are expected to automate most of these tasks, thus reducing human intervention and increasing system reliability. Some of these tasks pose significant dangers to their operators in manned systems, which restricts their applications to dull, dirty, and dangerous operations of unmanned systems [16]. Therefore, implementing such technology and making it technically feasible and mature enough to ensure higher safety and system reliability still remain longstanding issues. The performance of unmanned systems should be improved to be equal to, or even to overcome the difficulties faced in, manned systems. This may not be the case today for all the applications, but it will inevitably become a reality due to the continuous evolution of this technology.

Understanding the advancements brought by autonomous vehicles in ocean engineering is essential for gaining clear insights

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into the present and future requirements that need to be fulfilled in the ocean domain. The new requirements and concerns that emerge every day due to the continuous development of the ocean engineering make it difficult to describe or predict the future of autonomous vehicles in the ocean domain. However, because of the vast employment opportunities and resources that the ocean brings to humans, the ocean engineering has become one of the most important fields that is worth studying.

Application of autonomous vehicles is gaining popularity in ocean engineering to perform the most common tasks such as ocean monitoring [17], underwater ocean exploration [18], pollution monitoring [19], and environmental monitoring [20], among others. Through the application of these vehicles, every function of the ocean engineering that has the potential to be performed automatically can be made autonomous. Thus, their application decreases the intervention of humans in performing these tasks, as mentioned earlier, and at the same time increases the possibility of humans to completely rely on these autonomous systems to perform such tasks.

The emerging military applications in the ocean domain can also reduce human intervention in potential military conflicts. Some of the current military applications are intelligence, surveillance, and reconnaissance (ISR) [21–24], mine warfare (MW) [25, 26], and anti-submarine warfare (ASW) [27, 28], among many others. While armed conflicts between countries should be decreased and, if possible, eliminated, it is crucial to minimize casualties if conflicts do occur.

When discussing about autonomous vehicles, we refer to three main operational domains, namely air, surface, and subsurface. Because of the current decrease in the manufacturing cost and the prevalence of advanced knowledge among academicians and experts in different industries, it is possible to manufacture affordable vehicles capable of performing very advanced tasks at low cost by incorporating algorithms into them [29, 30]. The efforts of academicians and industry experts have led to the spread of relevant knowledge in the human society, thereby decreasing the research and development costs over time.

This article analyzes the current state of autonomous vehicle applications in the ocean engineering, providing insights into how their inclusion has revolutionized the field in recent years. Similar to other engineering fields, the progress of autonomous vehicle applications may take time to become sophisticated and fully aligned with current legal frameworks. Their present capabilities may not yet be sufficient to meet the demands of the ocean domain. Due to the vast number of applications, it is nearly impossible to address them all, but the most important ones will be properly described and analyzed. Additionally, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis [31–33] was proposed to better understand the current state of the use of autonomous vehicles in ocean engineering. Through this analysis, it is possible to understand the current scenario and adapt a proper strategy to maximize the existing strengths and opportunities and deal with the weaknesses and threats.

The article is structured as follows: The introduction describes the topic, contributions, and objectives. Section 2 discusses ocean engineering and autonomous vehicle applications, providing essential insights into the field. Section 3 offers a detailed analysis and discussion of the current and future states of the field based on the proposed SWOT analysis. Finally, Section 4 presents the conclusions.

2. Ocean engineering and autonomous vehicles

Two different terms are commonly used regarding engineering in the maritime domain: (i) marine engineering and (ii) ocean engineering. Marine engineering typically focuses on the design, construction, operation, and maintenance of ships [34]. On the other hand, ocean engineering involves integrating elements from various traditional engineering disciplines and applying them in the ocean domain to perform the needed tasks [4]. If adequately adapted, every engineering discipline can bring advantages to the necessary actions in the marine environment. Our focus will be on ocean engineering, giving clear insights into the major tasks performed.

Countries with coastal regions have the responsibility of managing their exclusive economic zones (EEZs), which extend up to 200 nautical miles from the baseline, as defined in the United Nations Convention on the Law of the Sea (UNCLOS) [35–37]. This grants these countries sovereign rights to explore, exploit, conserve, and manage natural resources within these zones. They also have jurisdiction over artificial islands, installations, and structures, as well as authority over conducting marine scientific research and protecting and preserving the marine environment.

However, there is an additional challenge of reducing the cost of investment in the maritime domain in both defense [38] and industry sectors [39]. Therefore, one of the most important factors to consider here is investing in autonomous vehicles, which can help lower costs as well as perform tasks more efficiently. The current growth in the number of companies that provide commercial off-the-shelf (COTS) autonomous vehicle solutions has also expanded the range of applications for the common user and improved cost-effectiveness [40, 41].

Autonomous vehicles are mobile robots capable of performing fully autonomous tasks [42]. The applications of autonomous vehicles are expanding almost daily in different fields [43], and ocean engineering is no exception. The future certainly lies in the autonomous domain, guaranteeing the need for less human intervention and ensuring more safety in executing dangerous tasks. Efforts should be made to automate manual tasks to improve the system reliability. A mature and developed autonomous system can decrease the susceptibility of humans to accidents when involved in dangerous tasks [44, 45], thus improving the overall system reliability.

The existing regulations, such as the International Convention for the Safety of Life at Sea (SOLAS) [46] and the International Regulations for Preventing Collisions at Sea (COLREGS) [47], were established before the emergence of autonomous technology. These regulations are designed to set safety equipment and procedures, navigation rules and lights, and signals and sounds assuming the presence of humans onboard [48]. The developed technology must be safe and compliant with international maritime law, which is an important issue that needs to be addressed because its operation becomes impossible without fulfilling these conditions.

It is important to consider liability and accountability when dealing with accidents involving autonomous vehicles [10, 49]. It is necessary to define civil and criminal liability clearly in such cases. The transition from human-operated to autonomous vehicles raises questions about who should be held liable, such as the manufacturers, operators, or system developers. From another perspective, ethical concerns include the direct decrease in maritime job availability, the environmental impact of increased autonomous vehicles, and decision-making in emergency situations [50, 51].

As our reliance on computer systems and software applications for data collection and processing increases, it is crucial that data protection and privacy of these systems should be prioritized [49]. This involves complying with data protection regulations such as the General Data Protection Regulation (GDPR) in Europe, especially for operations that span international waters and multiple jurisdictions. Since autonomous vehicles must communicate with each other as well as with control stations to retrieve data when needed, they are naturally vulnerable to cybersecurity attacks. Hence, it is essential to ensure a robust system architecture that guarantees security against such attacks, which could compromise their operational integrity, safety, and reliability. Such vulnerabilities could result in unauthorized control, data breaches, or sabotage, leading to accidents, environmental damage, and, in some cases, loss of lives [52, 53]. Therefore, implementing robust cybersecurity measures such as encryption, intrusion detection systems, and regular security updates is essential to protect these vehicles from potential threats [54].

The interoperability between different systems and manufacturers is crucial. Sharing data between systems can reduce the likelihood of accidents and improve the information used in autonomous tasks, thus enhancing reliability [55, 56]. Seamless communication and integration among various autonomous vehicle systems and components are essential for better coordination, situational awareness, and safety. Standardized protocols and open communication standards are necessary for achieving this interoperability, enabling diverse systems to work together efficiently and effectively [57].

Some of the current applications of autonomous vehicles in ocean engineering are detailed in **Table 1**. Autonomous vehicles are widely used in various applications, though they do not yet fully operate autonomously in all cases due mainly to their technological limitations or legal constraints. Apart from its advantages, a large-scale use is still a question to take into account [58, 59], since the discussion is not only about performing tasks autonomously but also about making it capable of interacting with other platforms and performing, for example, obstacle avoidance [60] or even working in a swarm of vehicles to accomplish a common task [61, 62].

Table 1 • Examples of ocean engineering applications and the tasks already performed by autonomous vehicles

Field	Description	Autonomous vehicles' application examples
Offshore structures	Design and construction of offshore platforms [4, 63]	Inspection and maintenance [64, 65]
Underwater acoustics	Communication, navigation, and mapping, among others [66, 67]	Acoustic mapping and communication networks [68–70]
Marine renewable energy	Harness energy from waves, tides, and thermal gradients [71, 72]	Maintenance of renewable energy systems [73–75]
Marine environmental pollution	Monitoring, prevention, and mitigation [76, 77]	Pollution detection and cleaning [19, 78]
Marine infrastructures	Designing, constructing, and maintaining infrastructures [79, 80]	Infrastructure inspection and maintenance [81, 82]
Marine natural resources	Identification and exploration [1, 83]	Deep sea mining exploration [84, 85]
Oceanographic applications	Scientific study of the ocean's physical, chemical, biological, and geological aspects [86, 87]	Monitoring, exploration, and research [88, 89]

Autonomous vehicles in ocean engineering, like other complex systems, rely on a combination of scientific and technological approaches to effectively operate in the various domains—air, surface, and subsurface. In underwater operations, these vehicles typically use sonar and acoustic communication systems to navigate and gather data, thus overcoming the challenges faced in the underwater environment [90, 91]. Surface and aerial autonomous vehicles use advanced navigation systems such as the global positioning system (GPS) and radar to perform navigation [92–95]. The operational range of these vehicles can be extended by using energy storage technologies with higher capacities, e.g., high-capacity batteries, or by utilizing renewable energy sources [96–99].

Autonomous vehicles are starting to play a critical role in military operations by providing advanced capabilities across different domains. In the aerial domain, they are commonly used in ISR operations, as they provide real-time data and reduce risks associated with having human pilots onboard [100, 101]. In the surface domain, they usually perform mine detection, patrolling, and logistic support tasks, enhancing operational efficiency and safety in hostile environments [101–103]. In the underwater domain, they are commonly used for tasks like mine sweeping and surveillance [101, 104–107]. Autonomous vehicles rely on algorithms and applications that enable unmanned operations, which makes them essential assets in modern military strategies.

Ocean engineering applications have become more efficient and effective due to recent advances and the increasing use of autonomous vehicles. Sensor technology is also progressing, enabling small payload autonomous vehicles to utilize it [108, 109]. The most frequently used sensor technologies in the ocean domain are sonar, Light Detection and Ranging (LiDAR), and cameras [107, 110]. The growing processing power available onboard these autonomous vehicles is crucial, necessitating more complex algorithms and proper data fusion from multiple data sources.

Artificial intelligence (AI) and machine learning (ML) are also changing the way we understand and use data and are frequently incorporated into our daily lives [111]. The field of autonomous vehicles is no exception, as AI and ML can enhance vehicle performance over time by learning from data obtained, for example, previously or even during operation [112, 113]. These algorithms are valuable for improving the vehicles' immediate operation and can predict maintenance needs and reduce system downtime [114, 115].

One of the most promising future developments in the technology is quantum sensors [116] which can be used to obtain images with higher precision. On the other hand, autonomous vehicles are emerging as another promising technology that can operate in multiple domains such as air, surface, and subsurface, thus providing higher flexibility and more possibilities for each vehicle platform. It is challenging to predict the precise technological direction autonomous vehicle technologies will take due to rapid technological advancements and uncertainty. With new opportunities and advancements arising every year, the future is unpredictable.

3. Strategic analysis and discussion

It is important to understand the current scenario of using autonomous vehicles in the ocean engineering to define a proper strategy for the future. The success of a strategy lies in the way it is executed rather than its content [117, 118]. To be successful, a global strategy should comprise realistic objectives and long-term goals. The SWOT analysis is only the beginning of a strategic planning process. Continuously analyzing and adjusting its content is crucial in a dynamic environment. After defining a strategy, the primary challenge lies in its implementation [119]. Using appropriate performance metrics based on clear strategic objectives is critical to evaluate and control the strategy implementation [120, 121].

The SWOT analysis is a strategic planning tool used to understand an organization, a project, or a business venture and enhance its development [31–33]. It helps assess the internal and external factors impacting an entity's success. Strengths and weaknesses are internal factors, while opportunities and threats are external factors. Strengths and weaknesses refer to internal characteristics or resources that can provide advantages or disadvantages, and opportunities are external factors that can contribute to success. On the other hand, threats are external factors that can lead to failure. It is important to conduct a SWOT analysis when analyzing an organization that involves in ocean engineering and uses autonomous vehicles. This analysis should be updated in response to any major environmental changes. From the performed analysis and state-of-the-art review, the identified strengths represent positive internal factors, weaknesses represent negative internal factors, opportunities represent positive external factors, and threats represent negative external factors. From the description provided in this article, a SWOT analysis has been derived, offering valuable insights based on the evaluation and analysis of the environment.

Strengths of autonomous vehicles' implementation in ocean engineering

- **Efficiency and reliability**: Autonomous vehicles can perform highly precise and reliable tasks, such as inspection and maintenance, among others, and reduce the occurrence of human failure [5].
- **Safety**: Autonomous vehicles can perform dangerous and hazardous tasks, thereby minimizing the risk to human operators [16].
- **Cost-effectiveness**: Advancements in technology have made autonomous vehicles more affordable and accessible [29].
- **Innovation and development**: Continuous improvements and technological advancements are expanding the capabilities of these vehicles [7].

Weaknesses of autonomous vehicles' implementation in ocean engineering

- **Technical maturity**: Some emerging technologies may not be fully developed, which can have impacts on the reliability and performance of autonomous systems [94].
- **High initial investment**: Even though there are long-term cost savings, the initial investment for the development and deployment of autonomous systems can be substantial [30].
- **Complexity of integration**: Integrating autonomous vehicles into existing systems and infrastructure can be a complex and challenging task [56].
- **Maintenance and Support**: Ongoing maintenance and the need for specialized support can be expensive and require a lot of resources [122].

Opportunities of autonomous vehicles' implementation in ocean engineering

- **Environmental monitoring**: Autonomous vehicles have the potential to improve monitoring and protection of the marine environment [20].
- **Resource exploration**: Autonomous vehicles can greatly enhance the efficiency of searching for and identifying underwater natural resources [123].
- **Sustainable energy development**: Autonomous systems can help develop and maintain sustainable ocean energy sources [15].
- **Regulatory advancements**: Developing new laws can make it easier to deploy and operate autonomous vehicles [9].

Threats of autonomous vehicles' implementation in ocean engineering

- **Regulatory hurdles**: Legal and ethical concerns, particularly related to liability and responsibility, can impede the adoption of autonomous systems [8].
- **Technological limitations**: The fast pace of technological advancement can lead to obsolescence and require continuous updates [124].
- **Security risks**: Autonomous systems can be vulnerable to cyber-attacks and other security threats [54].
- **Environmental impact**: There is a possibility of unforeseen environmental impacts resulting from the implementation of new technologies [125].

A SWOT analysis [32] is helpful for analyzing the environment. Here, the environment represents the dynamic context in which an organization operates. As described before, it includes internal strengths and weaknesses that can impact its capabilities, as well as external opportunities and threats that can influence its strategic decision-making and long-term success. However, consistently exploring and updating knowledge about the current environment, as it is highly dynamic, makes it possible to better understand the interactions between opportunities, weaknesses, strengths, and threats. The presented SWOT analysis is a suggested proposal based on the analysis conducted in this article. It aims to extract important information that can be utilized in defining an appropriate strategy for future implementation.

In summarizing the SWOT analysis, autonomous vehicles have several strengths, including efficiency, reliability, safety, cost-effectiveness, and innovation. However, they also have weaknesses due to technical immaturity, high initial investment needs, integration complexity, and maintenance costs. Opportunities exist in environmental monitoring, resource exploration, sustainable energy development, and regulatory advancements to support autonomous operations. Threats come from regulatory hurdles, technological limitations, security risks such as cyber-attacks, and potential environmental impact from widespread use. It is essential to address weaknesses and capitalize on opportunities. Thorough resource exploration and implementing sustainable energy solutions can reduce initial investment and maintenance costs. Regulatory advancements must also be implemented to mitigate existing threats.

The use of autonomous vehicles in ocean engineering holds great potential for development and survival of humans, as the ocean plays a crucial role in both. Therefore, there should be a clear focus on their development. Similar to the applications of any field, a fast implementation does not guarantee success. As in every field, a fast implementation without a proper strategy does not guarantee success. Hence, the focus should be on a solid and correct implementation, ensuring technological maturity and legal regulation to prevent accidents or drawbacks that could hinder the implementation and use of autonomous vehicles.

4. Conclusions

Autonomous vehicles demonstrate their potential in ocean engineering by enhancing efficiency, reliability, and safety of their applications while reducing human involvement. The degree of autonomy is continuously increasing, although some operations cannot be fully performed right now, primarily due to technological or legal constraints. This study focuses on the progress and current applications of autonomous vehicles in offshore structures, underwater acoustics, marine renewable energy, and environmental monitoring, among other areas.Some military applications were also explored, as employing autonomous vehicles without human intervention to perform necessary actions reduces human losses in combats. However, challenges remain, such as current technical immaturity, high initial costs, integration complexity, and ongoing maintenance costs. The performed SWOT analysis explains the strengths, weaknesses, opportunities, and threats of implementing autonomous vehicles in ocean engineering. The identified strengths include improved efficiency, reliability, safety, and cost-effectiveness. Weaknesses entail the need for significant investment, technical immaturity, and integration complexity. Opportunities can be found in environmental monitoring, resource exploration, sustainable energy, and regulatory advancements. Threats encompass regulatory hurdles, technological limitations, security risks, and potential environmental impacts. Implementing autonomous vehicles in ocean engineering requires continuous technological advancements, robust regulatory frameworks, strategic planning, addressing weaknesses, and minimizing threats for successful and sustainable implementation. The development and integration of autonomous vehicles hold great promise for the efficient and responsible use of ocean resources. Another important and possible approach for the future is enhancing safety at sea by using autonomous vehicles to better understand marine conditions and by increasing environmental investigations to detect hazardous artifacts such as explosives or lost chemical canisters. Although this aspect is not typically a focus for hydrographers or environmental investigators, it holds significant potential for exploration and safety improvements.

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