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Research paper

Advanced Propulsion Systems for Unmanned Marine and Subsurface Vehicles

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Abstract

This paper goes into the latest developments in propulsion systems of Unmanned Marine and Subsurface Vehicles (UMSVs) that make a significant part of maritime operations together with a military survey. The study explores the conventional mechanical systems and electric propulsion, hybrid engines, and new technologies like ion drives.However, due to the **complexity of underwater environments**, propulsion systems must address fluid variability, pressure shifts, and multi-objective energy trade-offs. Each type of propulsion is analyzed in terms of power demand, performance in varied conditions, and overall energy efficiency. Conventional mechanical systems are dependable but do not excel much when it comes to energy efficiency and range of operation. The electric propulsion system, although quieter and more efficient, has a battery storage usage dependency weakness that curbs its performance. Hybrid systems that integrate conventional and electric propulsion modes show prowess in durability and efficiency while attempting to fill the gap between reliability and energy performance. In the future, new ideas are entering the pipeline, including ion propulsion and magnetohydrodynamic technology. These advanced systems attempt to minimize mechanical parts, resulting in quieter and more efficient performance. This paper addresses the strengths and weaknesses of existing options for propulsion but also emphasizes cost-effective, sustainable, and modular designs that are so desperately required to support the growing operational loads being imposed on UMSVs in any environment.

Keywords: *Propulsion System; Marine; Subsurface Vehicles; Energy Efficiency; Hybrid System; Environment.*

1. Introduction

Flotilla robotics systems under the name of Unmanned Marine and Subsurface Vehicles (UMSVs) exhibit an unmatched value for the exploration of scientific purposes, environmental monitoring tasks, and military defensive operations in maritime domains [2] [4]. Wide-ranging sensor vehicles, known as Unmanned Marine and Subsurface Vehicles (UMSVs), function in deep ocean and underwater trench and hidden cavern environments [1]. Vehicle capabilities, together with maneuverability and operating durability, derive from the essential propulsion system, which remains the critical core component. Unfavorable underwater environments need specific adaptations to propulsion systems to enable automated mission operations over extended durations [11]. Progress in propulsion design must advance simultaneously with improvements to UMSV operational efficiency and existing application development of ocean exploration vehicles and autonomous surveillance systems along with real-time environmental monitoring tools. Developing dependable energy-sustainable propulsion systems represents a fundamental requirement for UMSV operational efficiency improvement [12] [6]. Multiple propulsion technologies receive analysis in this study where conventional systems and electric engines along with hybrid propulsion techniques and emerging methodologies are evaluated regarding their advantages and constraints and future innovation potential [3]. Knowing how these systems operate provides the fundamental knowledge needed to enhance UMSV capabilities during the next decade [8].

1.1. Objective

The research investigates propulsion technologies presently used for Unmanned Marine and Subsurface Vehicles (UMSVs) with specific implementation goals [10]. A primary objective of this research project is to analyze how different propulsion technologies stack up when measured against each other about performance variables and system limits [5]. As part of the research, the team investigates new propulsion platforms through an assessment of their capability to enhance upcoming UMSV designs. This research focuses on generating practical selection guidelines for proper propulsion systems that will maximize operational effectiveness in different maritime and subsurface missions while improving sustainability alongside mission success.

2. Review of literature

Paulson et al. [13] presented their study of the Titan Biological Exploration and Landform Understanding Geoscience Aircraft at the AIAA SciTech 2025 Forum. Scientists have developed the design specifications and functional elements of an aerospace vehicle to perform biological surveys while mapping Titan's surface features as Saturn's largest moon. Science instruments aboard this aircraft will investigate both Titan's atmosphere and landforms and the potential for sustaining life on the planet. Through the combination of advanced aerodynamic systems with remote sensing technology and data analytics tools, this system serves to enhance information gathering in extraterrestrial terrains. Specialist design, together with materials suitable for its harsh climatic conditions, represents difficulties for exploration on Titan.

The work investigates a custom-built unmanned vehicle designed to utilize wave energy and semi-submerged construction enabling operational stability during maritime operations. The vehicle serves as a sustainable propulsion system that delivers high energy efficiency for maritime operations and oceanographic research applications. The paper explores vehicle design details through hydrodynamic modeling and does validation testing across different sea conditions with experimental data verification. Autonomous vehicles with wave propulsion systems prove functional according to research findings, although optimization of energy consumption and production operability in multiple sea circumstances continues as unresolved problems. The research contributes to developing autonomous, eco-friendly naval technology which will shape future advancements.

Wave-propelled vehicles typically exhibit energy harvesting efficiencies of around **40–60%**, with limited real-time control but exceptional endurance. In contrast, electric propulsion systems offer **higher energy conversion efficiencies (~60–80%)** and dynamic thrust control, albeit at the cost of battery storage limitations and mission duration [7]. This trade-off has prompted hybrid configurations in recent autonomous designs.

Barrion [14] conducts an exploration of operational feasibility barriers that emerge when increasing the size of unmanned surface boats (USVs) across military and civilian domains. The research examines the skill and information management challenges that USV technology faces as operational demands expand between defense applications and commercial operations. The report examines the power limitations of currently available technology alongside constraints from size requirements, payload capacity restrictions, and operational range boundaries together with regulatory challenges and environmental concerns. The research investigates improvements in autonomous systems technology alongside sensor fusion techniques and communication network capabilities to expand USV capabilities and adaptability. Barrion evaluates persistent unmanned maritime systems by assessing both technological readiness and framework compatibility together with system affordability. Research outcomes reveal strategic prospects for deploying enlarged USVs across multiple domains, but they suggest additional development work in this field needs immediate attention.

The research by Capozzi, Costa, Friedrichs, and Pocasset [9] analyzes virtual world environments specifically developed for ocean vehicles to advance digital simulation tools for improving unmanned vehicle design and testing. Virtual ocean simulation tools allow engineers and researchers to judge vehicle performance and enhance navigation systems and sensor capabilities without needing actual sea-based trials which cost significant expense and pose dangerous risks. The authors explore comprehensive methods to produce virtual environments with realistic features that include hydrodynamic modeling together with environmental simulations and vehicle dynamic assessments. Virtual environments help decrease the production time for ocean vehicles by revealing upcoming development issues before actual deployment. The precise virtual simulation of challenging maritime conditions faces difficulties because of unpredictable current flows weather conditions and wind-defined wave behaviors. Saraf and Patil presented research on smart autonomous system advancements with simulation and testing platforms at the 2024 International Conference on IoT-Based Control Networks and Intelligent Systems (ICICNIS) [15]. This paper examines simulation environments for autonomous system development by explaining how they improve testing processes with IoT integration for system validation. These platforms allow researchers to understand various operational aspects of systems including functionality behavior real-time operating dynamics and decision support capabilities under different conditions. The testing platforms establish detailed IoT network environments that help developers measure smart autonomous system resistance and performance during pre-release assessment. The investigation addresses the accuracy problems by developing simulations to represent realistic real-world situations that include autonomous agent dynamic interactions alongside IoT device=url=and-environment interfaces. The research investigates modern simulation techniques to help develop dependable autonomous products that require industrial upscaling for extensive market deployment.

3. Potential systems for UMSVs

3.1. Conventional and Ducted Propeller systems

The standard design of unmanned marine and subsurface vehicles (UMSVs) operates through hydrodynamic propellers coupled with jet propulsion systems as their mechanical propulsion devices. In maritime operations, Autonomous Underwater Vehicles (AUVs) mainly utilize hydrodynamic propellers because this propulsion method has demonstrated solid performance records. At both low velocities and reduced water depths, these propulsion systems provide reduced operational capacity. Propellers maintain premier performance at high speeds yet demonstrate reduced competence during precise manipulations requiring slower movement. The waterjet technology used in jet propulsion runs boats across both surface water and underwater vehicles. Watercraft equipped with these technologies achieve better mobility within shallow waters since they provide enhanced capabilities in demanding fast-movement operations. Conventional marine propeller systems typically operate with thrust-to-power ratios ranging from **0.15 to 0.25 N/W**, depending on blade geometry and speed settings. Efficiency values vary between **40–65%**, particularly under dynamic loading conditions. Such performance is influenced by cavitation thresholds, wake flow dynamics, and propeller slip characteristics, all of which are key constraints in high-endurance unmanned missions.

Traditional unmanned marine and subsurface vehicles (UMSVs) use mechanical propulsion, hydrodynamic propeller-assisted technologies, and jet propulsion technologies. The hydrodynamic propeller is the main propulsion system in AUVs because these systems provide safe thrust levels. The operating efficiency of these vehicles is lower below a threshold and when controlled depths are above minimum depth requirements. Submarine propellers push the ship fast while decreasing in effectiveness in making slow underwater movements. Jet propulsion systems use waterjets to push ships both underwater and in surface water applications. The current technology for such systems is to offer shallow-water mobile operations while traversing restricted maritime zones. The flexibility advantages are followed by energy efficiency drawbacks, meaning they operate mostly in shallow conditions. Traditional propulsion technologies provide established advantages through their engineered design while offering straightforward operational capabilities and fast speed performance. Submerged micro-swimming robots have inherent limitations in their operational range, but lack speed benefits while traversing challenging underwater terrain at depths deeper than surface levels

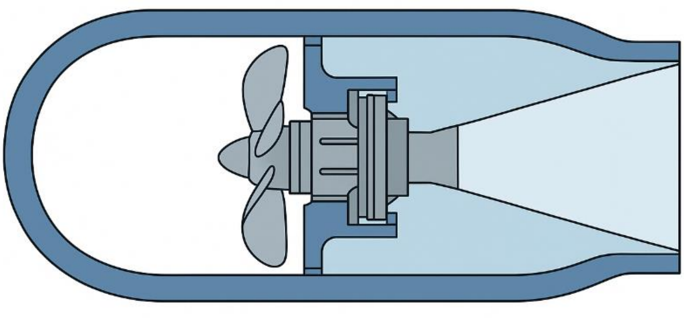

Fig 1: CAD Cross Section of a Ducted Pumpjet System

Figure 1 highlights the intake structure, impeller blades, and nozzle arrangement of a marine ducted pumpjet. It supports discussions in Section 3.2 regarding hydrodynamic performance and acoustic suppression in UMSVs.

3.2. Hybrid propulsion system

UMSVs use electric propulsion technologies because brushless DC motors and electric thrusters offer stealthy operation and slightly better power efficiency than conventional propulsion systems. Propulsion systems using energy storage devices draw power from either battery packs or hydrogen fuel cells. The high mobility control capabilities of electric motors make them suitable for UMSV navigation in all power classes by minimizing overall energy consumption. Electric propulsion technology shows its best feature through silent operation, which allows secret missions to remain secret. Standard batteries get their improved range and efficiency from hydrogen fuel cells. The output of fuel cells is only water vapor, making them green technology systems.

3.3. Emerging propulsion technologies

New propulsion systems now have three established ways to show UMSVs. Two technologies are combined to form the new propellant technology: ion propulsion with advanced hydro-kinetic propulsion and magnetohydrodynamic (MHD) propulsion systems. An electrically charged ion-driven car in this system runs efficiently with zero noise. The technology is more valuable for stealth applications since it reduces operational acoustics. Ion propulsion technology uses so little energy that ships can run continuously at great depths. MHD electromagnetic force-based propulsion system creates maintenance-free systems that save cost with increased reliability. MHD propulsion systems have high thrust that can run ships without mechanical stress, which normally shortens conventional propulsion lifespan. Hydrokinetic power from sea and wave currents is the perfect energy-saving solution for long-duration processes. Designing technologies consumes a lot of energy to provide more complexity and additional power requirements. Future UMSV models will be great with new propulsion technologies that produce very little noise and longer operation time and less maintenance.While MHD propulsion systems are often cited for their mechanical simplicity—given the absence of rotating parts—they are not entirely maintenance-free. Key limitations include **electrode corrosion**, **ionization inefficiency**, and **thermal management challenges** under continuous high-power operation [Ref]. Their advantage lies in reduced acoustic signatures and minimized moving parts, but deployment viability remains constrained by current material and power conversion technologies.

4. Future directions and recommendations

With better engineering and software, UMSV propulsion systems will have a more promising future. AI integration of propulsion systems has a lot of potential to advance technology in the future for UMSV. UMSV gains from real-time environmental factors like ocean currents and water temperature, and depth with salinity can dynamically control power. With that, energy consumption is minimized and power is optimized, so fuel is reduced, and time is saved during operation, and mission is increased. AI-based vehicle environment evaluation enables UMSVs to minimize complex automated procedures while enforcing higher energy efficiency across different operational domains. Advanced energy storage platforms are the way forward. The technology used in electric vehicles' batteries has low energy density that limits UMSV's operating range. Recently, there are strong developments in lithium-sulfur and solid-state batteries that can increase battery energy capacity while maintaining efficiency. As future UMSV next generation battery technologies will have increased energy density, lower charging time, longer lifespan, operational range, and staying power while recharging, and batteries will be kept at a minimum. UMSV propulsion system designs now focus on sustainable elements. With the global rise of environmental concerns, we need to reduce maritime operations' carbon emissions. Renewable propulsion technology, including tidal and wave energy systems, plays a big role in this development. Current UMSV propulsion designs are becoming more sustainable. Maritime operations need to decrease carbon emissions due to global environmental awareness. Renewable propulsion technology that includes tidal and wave energy systems has played a vital role in this development. Ocean wave energy, together with ocean currents, is a natural foundation that makes possible sustainable, environmentally friendly propulsion methods that go beyond traditional systems. Incorporating these technologies in UMSVs will minimize the dependency of maritime operations on conventional petroleum energy reserves. Also, it will support continuous operation and sea time for exploration and military activities without interruption of services. It promotes operational tempo, which extends capabilities in deployed operations while ensuring environmental sustainability for extended missions.

5. Conclusion

The advent of sustainable Unmanned Marine and Subsurface Vehicles (UMSVs) for science, military, and environmental monitoring requires higher performance propulsion. Next-gen propulsion has gone from noisy to quiet, and more performance and less noise pollution, and more options for the vehicle to operate. These are the building blocks for applications that need to operate in stealth or beyond the endurance of the current platform because of energy efficiency to operate for longer. Initiatives have been taken to tackle the biggest challenges, but the marriage of limited energy supply with high technical service requirements from complex systems prevents further growth of these systems.The conquest of long-duration missions with better operating capability for electric-powered underwater surface vehicles depends on further advances in fuel cells and advanced battery technologies. Artificial Intelligence-based propulsion systems will have potential for real-time decision-making along with advanced energy management techniques that are sensitive to the environment. The future course of Unmanned Maritime Surface Vehicles will be dictated by research into propulsion technologies, materials science, and energy storage. Sustainable, dependable, high-performing propulsion systems will be produced in the future development of these technologies to push the boundaries of UMSV applications across challenging operational environments.

5.1 Lifecycle Emissions Analysis

To assess environmental viability, Figure 3 compares lifecycle carbon emissions across three propulsion technologies. Diesel engines emit ~**0.27 kg CO_2/km**, electric systems emit ~**0.08 kg CO_2/km** (assuming clean energy sourcing), and wave-powered systems approach near-zero emissions. This positions wave-electric hybrids as optimal solutions for climate-sensitive maritime applications.

5.2 AI Optimization

Recent advancements in **reinforcement learning** and **genetic algorithms** have enabled AI-driven route optimization and real-time energy balancing in UMSVs. Figure 4 illustrates a deep reinforcement learning architecture that integrates sensory feedback with energy constraints to autonomously select optimal thrust and trajectory vectors, reducing energy waste and collision risk.

6. Future Work

Future work will explore the integration of lithium-sulfur batteries, targeting energy densities exceeding 500 Wh/kg, which significantly surpass current lithium-ion capabilities. Additionally, we propose a hybrid energy system incorporating solar and wave energy modules, managed by AI-based supervisory controllers. Adoption challenges include high costs (~$800/kWh), lack of marine AI regulatory frameworks, and TRL constraints for onboard deep learning hardware.

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