



Power and performance analysis of UUV motor systems with torpedo capabilities using to support the Indonesian navy's maritime operations

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Abstract

Unmanned Underwater Vehicles (UUVs) play a crucial role in modern naval operations, particularly in Intelligence, Surveillance, and Reconnaissance (ISR) and Anti-Submarine Warfare (ASW). Their stealth and long-range capabilities provide strategic advantages, yet extended missions pose significant challenges due to power limitations. This study proposes a novel approach to predicting and managing UUV battery capacity for missions lasting up to 30 days. Utilizing OpenModelica, we simulate various operational scenarios by modeling the Direct Current Permanent Magnet (DCPM) motor and its interaction with propulsion systems under different mission profiles including patrol, standby, and attack phases to estimate power consumption and optimize endurance. The results demonstrate key strategies for enhancing UUV autonomy and operational flexibility through advanced power management. These findings contribute to the development of more efficient UUV systems capable of prolonged underwater missions with minimal recharging.

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INTRODUCTION

Unmanned Underwater Vehicles (UUVs) have rapidly emerged as a cornerstone of modern naval strategies, especially for nations with vast maritime territories. These autonomous systems are pivotal in executing various missions, from Intelligence, Surveillance, and Reconnaissance (ISR) to Anti-Submarine Warfare (ASW). Their ability to operate stealthily, traverse long distances, and function autonomously provides significant strategic advantages, particularly in challenging and hostile underwater environments. Recent advancements in UUV technology have significantly expanded their operational capabilities, allowing these vehicles to perform complex tasks that were previously impossible or required manned submarines (Arif et al., 2023). Innovations in propulsion systems, energy management, and sensor integration have enabled UUVs to carry out extended missions, with some designs now capable of sustaining operations for months or even years without

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direct human intervention ([Zereik et al., 2018](#)). One of the primary challenges in deploying UUVs for extended missions is managing power consumption to ensure the vehicle can operate effectively over long durations without frequent recharging. This challenge is particularly pronounced in military applications, where uninterrupted operation is critical for mission success ([de la Vega et al., 2024](#)).

Several previous studies have modeled UUV propulsion systems using data-oriented approaches implemented in MATLAB. While this method enables power consumption estimation under various conditions, it presents limitations when dealing with complex physical representations of the system. Specifically, data-oriented modeling struggles to intuitively represent multi-component mechanical and electrical interactions within the propulsion subsystem ([Aslam et al., 2022](#)). To address this gap, our research proposes the use of OpenModelica, a modeling tool based on object-oriented modeling (OOM), which allows more structured, modular, and physically representative system descriptions. By utilizing OpenModelica, this study aims to model the propulsion system of UUVs more realistically and flexibly. We simulate various operational scenarios to estimate power consumption and identify the optimal conditions under which the UUV can maintain continuous operation without compromising performance ([Rupp & Reveles, 2020](#); [Fritzson et al., 2020](#); [Elmqvist et al., 1999](#)).

To provide context for the relevance of this research, it is important to discuss current UUV applications and their typical mission profiles. UUVs play a vital role in a range of military and commercial operations, including Intelligence, Surveillance, and Reconnaissance (ISR), Anti-Submarine Warfare (ASW), mine detection, environmental monitoring, and underwater infrastructure inspection ([Wei et al., 2021](#)). UUV missions vary significantly in terms of duration and operational environments, spanning from shallow coastal waters to deep-sea deployments. These missions often face challenges such as limited communication capabilities and the necessity for autonomous decision-making ([Lee et al., 2023](#)). One of the primary challenges in these missions is effective power management. Due to limited battery capacity, energy must be used efficiently to ensure the UUV can complete its objectives without interruption ([Wang et al., 2022](#)). The findings of this study, which focus on power management and battery optimization, directly address these challenges. By enhancing power efficiency, UUVs can achieve longer mission durations, greater operational flexibility, and improved overall performance across a variety of applications. This paper thoroughly analyses the power and performance attributes of UUV motor systems that are equipped with torpedo capabilities. Our findings offer valuable insights for designing future UUV systems, especially those intended for long-term missions. By accurately predicting power requirements and efficiently managing battery life using object-oriented modeling techniques, we aim to develop UUVs with greater autonomy, operational flexibility, and resilience in diverse and challenging environments.

METHOD

The simulation focuses on the electric motor system, comprising two key subsystems: the conversion of electrical energy into mechanical energy and the subsequent transfer of this mechanical energy to the motor, initiating the rotational motion required to propel the UUV. These subsystems, illustrated in Figure 1, work together to achieve overall system performance. For this simulation, the gear ratio is set at 1:1, ensuring a direct rotational energy transfer from the motor to the propeller.

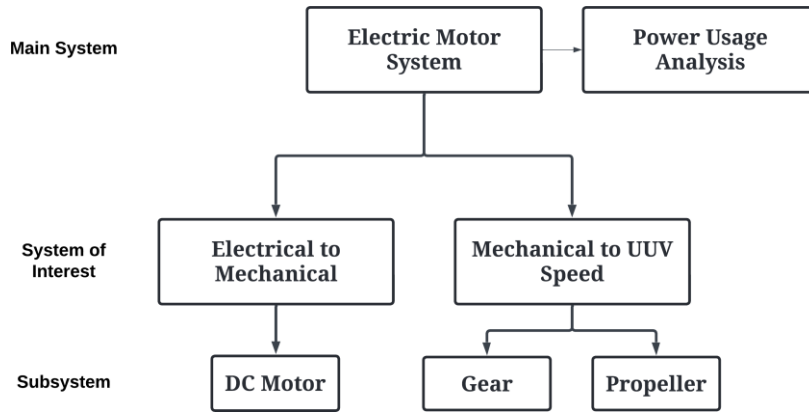


Figure 1. Diagram of Electric Motor System

Electrical Energy to Mechanical Energy

Converting electrical energy into mechanical energy begins with electricity flowing from the power source to the DC motor. The key equations governing this process are as follows:

$$V = I \cdot R \tag{1}$$

Where V is the voltage applied to the armature coil of the DC motor, R represents the resistance of the armature coil, and I is the current flowing through the coil. This equation describes the fundamental relationship between voltage, resistance, and current in a DC motor.

$$V_{induced} = \frac{d\psi_e}{dt} \tag{2}$$

The induced voltage ($V_{induced}$) is generated by the change in magnetic flux (ψ_e) within the motor. The term $\frac{d\psi_e}{dt}$ denotes the rate of change of magnetic flux over time.

$$\psi_e = L_e \cdot i_e \tag{3}$$

The magnetic flux (ψ_e) in the motor is a product of the inductance (L_e) and the current (i_e) through the motor’s coils. This equation links the magnetic properties of the motor to the electrical current.

$$V_{induced} = K_e \cdot \omega \tag{4}$$

The induced voltage ($V_{induced}$) is also directly proportional to the angular velocity (ω) of the motor’s rotor and the motor constant (K_e). This relationship illustrates how the engine’s rotational speed affects the induced voltage.

$$\tau = K_t \cdot I_a \tag{5}$$

The torque (τ) produced by the motor is proportional to the armature current (I_a), with K_t being the motor torque constant. This equation explains how the motor’s torque is generated based on the current flowing through it.

$$\omega = \frac{d\phi}{dt} \tag{6}$$

Finally, the angular velocity (ω) is the rate of change of the angular position (ϕ) of the rotor over time. This equation defines the relationship between the rotational speed and the change in the rotor’s angle.

UUV Propulsion System Overview

A hybrid Unmanned Underwater Vehicle (UUV) relies on a propulsion system that typically includes a DC motor, gearbox, and propeller. Each component determines the vehicle's overall performance ([Carlton, 2018](#)). The DC motor is the primary source of mechanical power, converting electrical energy into rotational motion. This rotational motion is transmitted through the gearbox, which adjusts the motor's output speed and torque to match the operational requirements. Finally, the propeller converts this rotational energy into thrust, propelling the UUV through the water. Understanding the interaction between these components—particularly how the gearbox modifies the DC motor's speed and torque and how the propeller converts them into thrust—is essential for accurately calculating the UUV's speed and optimizing its performance ([Vertical Flight Society, 2020](#)).

Propeller Dynamics and UUV Speed Calculation

The propeller used in this system is based on a design from a MkXII torpedo featuring a propeller pitch of 30 inches. The relationship between the parameters that determine the UUV's speed is captured by the following equation:

$$V = \frac{p \cdot Engine_{rpm} \cdot (1 - slip)}{R_G \cdot C} \quad (7)$$

In this equation, the propeller pitch (p) refers to the distance the propeller moves the vehicle forward with each revolution. The engine speed ($Engine_{RPM}$) indicates the number of revolutions per minute of the engine, while the slip factor ($slip$) measures any inefficiency in converting rotational energy into forward motion. The gear ratio (R_G) defines how many engine revolutions are required to turn the propeller once. Finally, C is a conversion factor that adjusts the units of propeller pitch to match the velocity units, with a value of 1215.2 for nautical miles per hour.

Impact of Increased Mass on Propeller Pitch, Gear Ratio, and Propeller System

Increased mass in a hybrid UUV, such as when carrying a torpedo, impacts its propulsion system, requiring adjustments to propeller pitch, gear ratio, and overall propeller efficiency.

- a) Propeller Pitch: With added mass, the propeller must overcome more excellent resistance, possibly requiring a higher pitch to maintain speed. However, this increases motor load, so careful balance is needed to avoid inefficiency or overload ([Fossen, 2011](#); [Healey, & Lienard, 1993](#)).
- b) Gear Ratio: A heavier UUV demands more torque, which can be addressed by lowering the gear ratio. This increases torque but may reduce speed, requiring a trade-off based on mission needs ([Kim et al., 2011](#)).
- c) Overall Propeller System: The added mass increases drag and slip, reducing efficiency. Optimizing the propeller design and fine-tuning the gear ratio is essential to maintaining operational efficiency ([Feezor et al., 2001](#)).

Angular Velocity and Its Impact on Power Consumption

Before estimating the total energy consumption of a UUV, it's essential to understand the role of the motor's angular velocity in the power consumption equation. Angular velocity, often represented as ω , is the rate at which the motor shaft rotates, typically measured in radians per second. This parameter directly relates to the motor's revolutions per minute (RPM) and determines how quickly the motor converts electrical energy into mechanical energy ([Yang et al., 2019](#)).

The motor's angular velocity affects the power required to maintain the UUV's desired operational speed. Higher angular velocities generally result in higher power consumption, as the motor must work harder to overcome resistances such as water drag and any additional load from onboard systems or payloads. Understanding the relationship between angular velocity and power consumption can help provide more accurate estimates when planning for extended missions ([Sweeting et al., 2011](#)).

UUV Energy Management

Estimating total energy consumption is crucial for UUV missions to determine battery capacity. Mission duration varies, so understanding energy needs is essential to prevent power depletion ([Zhao et al., 2022](#)). First, assess the UUV's average power consumption, covering propulsion, sensors, communication, and other systems. Power usage fluctuates as systems don't operate at total capacity simultaneously, so average consumption provides a reliable estimate ([Yang et al., 2018](#)). Once established, multiply the average by mission duration to calculate total energy needs. Consider voltage and amp-hour ratings to ensure sufficient battery capacity. This process requires periodic reviews as mission conditions change, ensuring UUV reliability. Hybrid UUVs combine battery and fuel power are designed for long missions, such as surveys, surveillance, and mine countermeasures, lasting weeks or months ([Sweeting et al., 2011](#)). The hybrid system conserves energy by alternating power sources based on mission needs. A typical mission may involve patrolling within a 1-10 km radius or stationing on the seabed for up to 90 days ([Bae, & Hong, 2023](#)).

Motor RPM in Hybrid UUV Missions

Motor RPM is critical across various mission phases, impacting energy efficiency and operational effectiveness. During patrols within a 1-10 km range, the motor operates at a lower RPM, balancing speed (2-5 knots) with energy conservation ([Guo et al., 2024](#)). When stationed on the seabed, the RPM drops even further, allowing minor adjustments while conserving energy over 90 days.

In the event of a detected threat, the RPM rapidly increases to provide the necessary thrust during torpedo launches, enabling the UUV to target enemies up to 20 km away. Adjustments in RPM are also required to counteract the added drag and inertia from increased mass, such as when the UUV is carrying additional payloads. The RPM dynamically adapts to the specific demands of each mission phase, ensuring the UUV remains effective across various operational scenarios.

RESULTS AND DISCUSSION

Selecting the right simulation tool is crucial for modelling complex systems like a UUV. Signal flow-based tools, often used for control systems, model systems as interconnected blocks with defined inputs and outputs, offering straight forward computation ([Zhang et al., 2022](#)). However, OpenModelica, an open-source Modelica implementation, provides significant advantages for UUV modelling. Unlike causal signal flow-based tools, OpenModelica uses an equation-based (acausal) approach to model variable relationships without a fixed computation order. This collective equation-solving capability is ideal for simulating complex interactions in multi-domain systems like UUVs, where propulsion, hydrodynamics, and power management are interdependent. OpenModelica's open-source nature also supports greater customization and integration with other tools, making it versatile for adaptable research projects. While signal flow tools excel in control systems, OpenModelica is better suited for projects that require a holistic understanding of complex, interconnected systems like those in UUVs ([Swaminathan, & Saripalli, 2018](#)).

DC Permanent Magnet Motors for Hybrid UUV Propulsion

DC Permanent Magnet (DCPM) motors offer high efficiency across various operating conditions, making them ideal for Unmanned Underwater Vehicles (UUVs) on extended missions. Their ability to deliver precise speed and torque control ensures that UUVs can navigate accurately and efficiently in complex underwater environments. Additionally, DCPM motors boast a high torque-to-weight ratio, which allows for a compact and lightweight propulsion system. This is crucial for maximizing the UUV's payload capacity and operational endurance. The brushless design of DCPM motors significantly enhances their reliability by minimizing wear and reducing maintenance needs, which is especially important for ensuring durability in harsh underwater conditions ([Dastjerdi et al., 2018](#)).

The Modelica framework effectively captures the electrical, rotational, and thermal behaviours in the DC Permanent Magnet (DCPM) motor model used for the hybrid UUV. This model is part of the Electrical package, encompassing various DC machines and the overall power system. The model simulates critical performance aspects such as torque, speed, current, and associated losses. The armature voltage, representing the motor's electrical domain, is linked proportionally to motor

speed. Rotor inertia is crucial in modelling the rotational domain, accurately reflecting the motor's dynamics under varying load conditions (Swaminathan, & Saripalli, 2018).

A vital feature of the DCPM motor model is its ability to simulate the interaction between electrical flux and mechanical rotation, governed by the machine's air gap behaviour. The excitation current plays a fundamental role in this interaction, driving torque generation in the motor. Additionally, the model incorporates thermal components to account for heat dissipation due to frictional and electrical losses, ensuring a comprehensive simulation that mirrors real-world operating conditions. This integration of multiple domains allows for an accurate representation of the DCPM motor's performance within the UUV propulsion system (Vertical Flight Society, 2020).

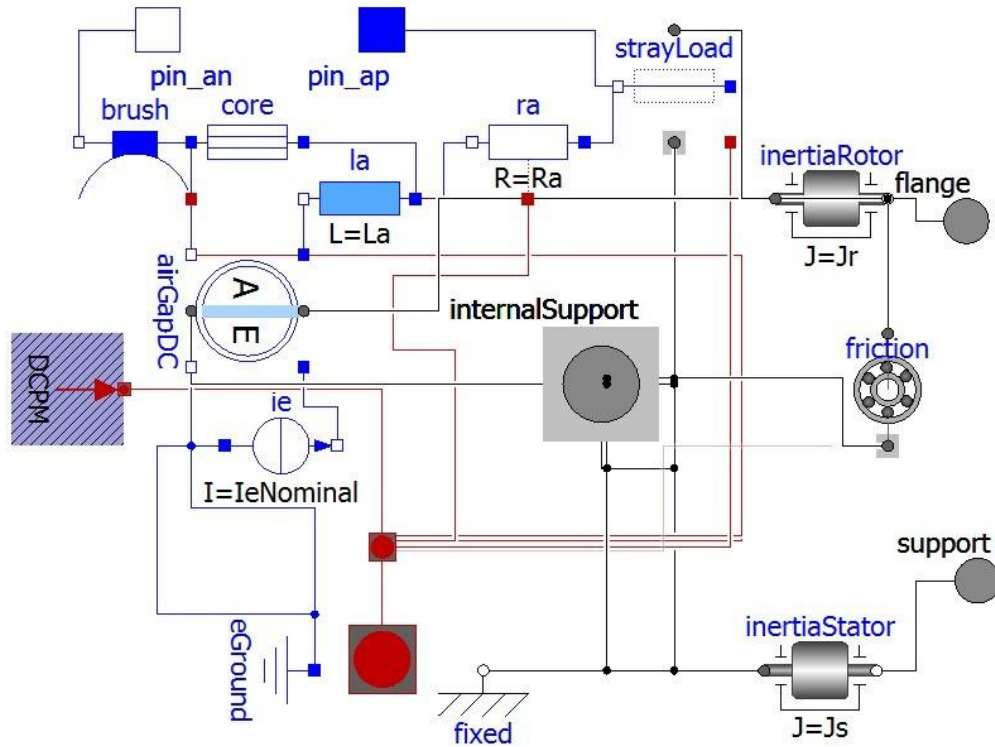


Figure 2. Diagram DCPM

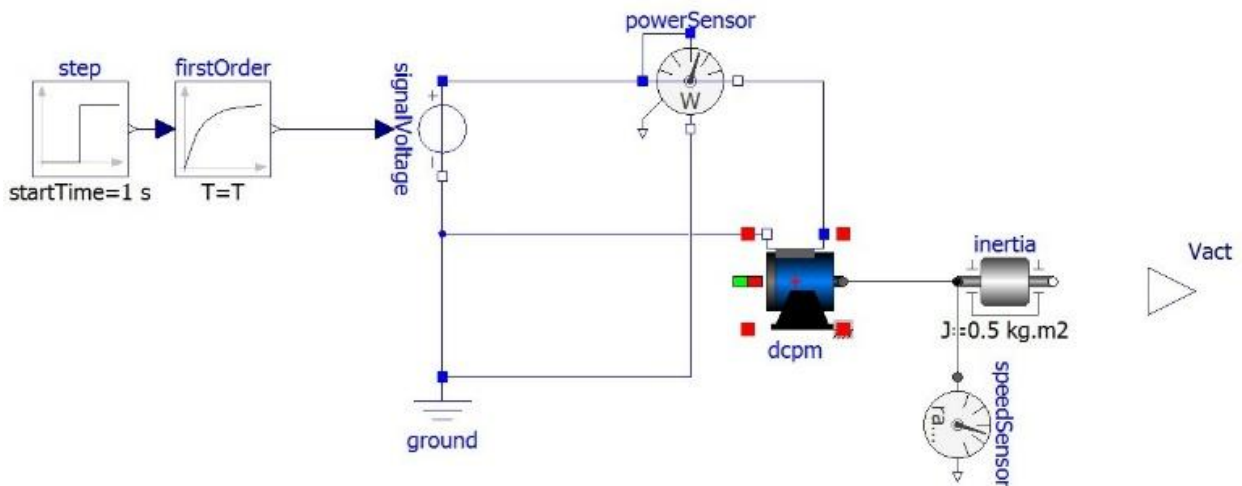


Figure 3. Diagram of Electric Motor System's Workflow

The DCPM motor model. Rotor inertia and air gap flux account for the thermal and mechanical dynamics that influence motor performance under various conditions. Figure 2 illustrates the model designed to simulate motor performance, considering critical aspects like torque, speed, current, and associated losses. The armature voltage represents the electrical domain and is proportionally linked

to motor speed, while rotor inertia captures the motor's rotational dynamics under different load conditions ([Vertical Flight Society, 2020](#)).

Input Signal and System Nodes

In the DCPM motor model, the input signal is a crucial factor influencing motor behaviour under various operational conditions. The system's workflow, depicted in Figure 3, begins with the Command and Control system, which generates an input signal based on predefined parameters. This simulation uses a step signal of 100 Amps as the input.

- a) **Signal Propagation Through the System:** The step signal is fed into the Signal Voltage component, generating a corresponding voltage. This voltage, capped at 120 Volts in the simulation, is essential for driving the motor. The voltage then passes through the resistor and inductor components, which modulate the signal before it reaches the DC Permanent Magnet (DCPM) motor.
- b) **Sensors and Measurement Points:** As the motor operates, various sensors monitor key performance metrics. The speed sensor measures the motor's angular speed (in radians per second), while the power sensor tracks the current, voltage, and power consumed by the system. These measurements are critical for evaluating motor performance and ensuring it operates within the desired parameters.

Simulation Result

Figure 4 illustrates the dynamic response of a UUV propulsion system. Initially, the propeller remains idle for 1 second before beginning its motion. The system then accelerates smoothly, reaching a maximum speed of 3 knots within 5 seconds.

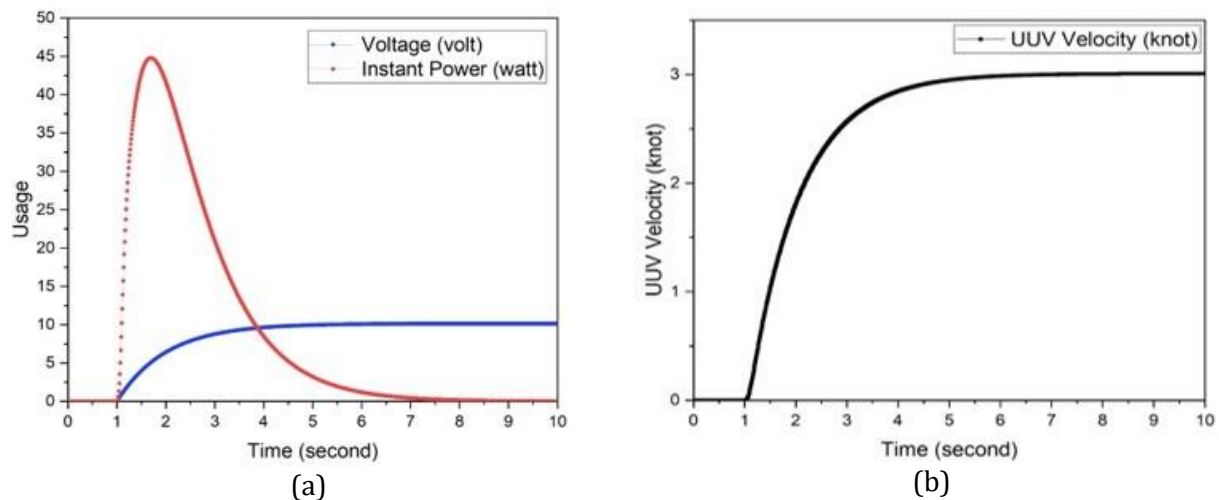


Figure 4. Simulation Results: UUV Speed (a) and Power (b) Dynamics

As the propeller starts, the power output peaks at 50 watts just 0.5 seconds into the motion, reflecting the motor's initial effort to overcome resistance. Subsequently, as the propeller reaches its maximum speed, the power output gradually decreases to zero over the next 4.5 seconds. This decrease demonstrates the system's stabilization and efficiency in maintaining the desired speed with minimal energy consumption. The workflow begins with the Command and Control system generating an input signal, which initiates the motor's operation as depicted in Figure 2. The motor then generates an RPM of 120, directly influencing the propeller's performance. This performance contributes to the dynamic response observed, showcasing how motor dynamics translate into operational efficiency for the UUV, as seen in Figure 3. This integrated approach highlights the importance of motor and propeller interactions in ensuring steady and efficient underwater operations.

Battery System Calculation for UUV Mission

Imagine a UUV preparing for an extensive mission. It begins with a 5-day journey to reach its initial patrol location. Once there, the UUV patrols a 10 km radius for 45 days, maintaining vigilance over the designated area. After completing this mission, the UUV must return to base, which takes 5

days. The UUV must operate continuously throughout this mission, relying solely on its onboard battery for power. When calculating the battery capacity required for this UUV mission, it's crucial to include the energy needed to move to the initial location before starting the patrolling phase. This movement phase also consumes power and must be accounted for in the total battery capacity. The basic formula used to calculate the required battery capacity (Capacity) in ampere-hours (Ah) is:

$$\text{Capacity (Ah)} = \frac{P_{\text{roam}} \cdot 1000}{V} \quad (8)$$

To calculate the total energy required (P_{roam}) in kilowatthours (kWh), the following formula is used:

$$P_{\text{roam}} = P \cdot T \quad (9)$$

Key inputs are necessary to calculate the required battery capacity for the UUV mission. The power consumption, denoted as P , is measured in watts (W) and varies depending on the mission phase. The duration, represented as T , is the time in hours each mission phase lasts. Finally, the battery voltage, denoted as V , is measured in volts (V). These inputs are essential for determining the total energy requirement and the battery capacity needed to sustain the UUV's operations throughout its mission.

As an example of battery calculation for a patrolling mission, the operation begins with a 5-day movement to the designated location. During this phase, the UUV consumes power at 50 watts while travelling at 3 knots, resulting in a daily energy consumption of 1.2 kWh and a total of 6 kWh over the 5 days. Next, the UUV conducts a 45-day patrol within a 10 km radius, maintaining the same power consumption. This phase requires 54 kWh, calculated as 1.2 kWh per day over 45 days. Finally, the UUV undertakes a 5-day return journey, consuming an additional 6 kWh of energy. In total, the UUV's energy requirement for the entire mission—including the initial movement, patrolling, and returning to base—amounts to 66 kWh. Thus, the required battery capacity would be:

$$\text{Capacity (Ah)} = \frac{66 \text{ kWh} \cdot 1000}{48 \text{ V}} = 1375 \text{ Ah} \quad (10)$$

After 30 days of patrolling, the hybrid UUV must strike a target at a distance of 20 km. During the patrol, the UUV operates at 50 W, consuming 36 kWh over 30 days. The UUV then accelerates to 35 knots for the strike, with the power demand increasing to 120 W, as shown in Figure 5. The strike lasts for 1 hour, requiring 0.12 kWh of energy. Unfortunately, the UUV is destroyed during the strike, preventing its return. The total energy needed for the mission, including the strike, is 36 kWh. With a base voltage of 48 V, the required battery capacity is approximately 752 Ah, ensuring the UUV sustains its mission up to the point of destruction.

CONCLUSION

This paper has presented a comprehensive analysis of power consumption in UUV electric motor systems using OpenModelica. The primary contribution of this research lies in the development and simulation of a propulsion system model that integrates mission-specific parameters with electrical and mechanical dynamics. Through scenario-based simulations, we demonstrated how precise modeling of Direct Current Permanent Magnet (DCPM) motors can lead to more efficient energy usage, directly contributing to extended mission durations.

The mission profiles tested—ranging from extended patrols to rapid torpedo strikes—validated the effectiveness of the proposed approach in managing battery life and maintaining propulsion efficiency. These findings address the critical research objective of enhancing UUV autonomy through optimized energy management. Furthermore, the use of an object-oriented modeling approach enabled a more holistic representation of system interactions compared to traditional signal flow or data-oriented models.

Despite these promising outcomes, the study is limited by the assumption of ideal underwater conditions and the absence of real-time feedback or environmental disturbances in the simulation. Future research should incorporate dynamic factors such as water currents, salinity, pressure, and

temperature variations to improve the model's fidelity. Additionally, integrating machine learning-based adaptive control strategies, hybrid power architectures, and advanced battery aging models would further strengthen the applicability of the framework. Field validation through hardware-in-the-loop or real-environment testing is also recommended to translate simulation results into operational reality.

AUTHOR CONTRIBUTIONS

Author of this article played an important role in the process of method conceptualization, simulation, and article writing.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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