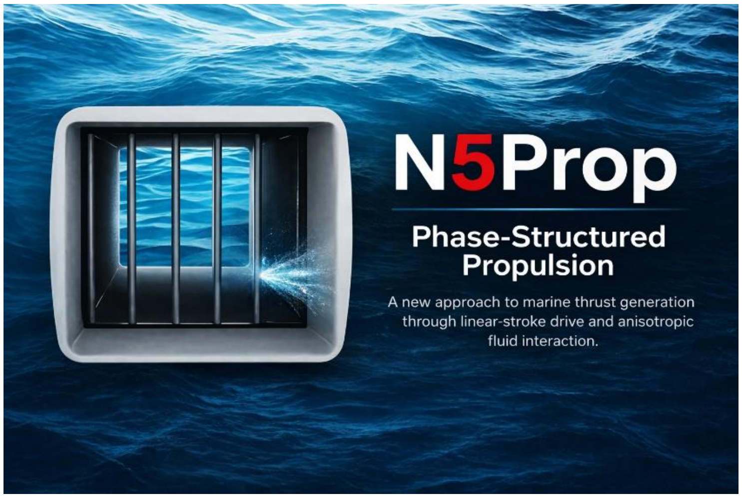
The future of propulsion is not in spinning faster — but in interacting smarter.



Phase-Structured Marine Propulsion

Linear-Stroke Electromagnetic Drive with Anisotropic Fluid Interaction for High-Efficiency UUV Systems

N5Prop Concept Paper

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Preface

From Rotational Propulsion to Phase-Structured Interaction

Propulsion systems across air and water domains have historically relied on continuous rotational interaction with a fluid medium. Whether implemented through propellers, turbines, or jet systems, thrust has been generated by persistently imparting momentum to the surrounding fluid—often with significant energy losses embedded in the process.

In parallel work on Phase-Adaptive Drone Propulsion, we introduced a different paradigm: propulsion as a **time-structured interaction with the medium**, where thrust generation is divided into distinct phases rather than applied continuously. In this framework, efficiency arises not from sustained force, but from **controlled alternation between high-coupling propulsion phases and low-resistance reset phases**, synchronized with the fluid environment.

The Linear-Stroke Marine Propulsion system presented in this document is a direct realization of this same principle in a denser medium. The anisotropic propeller and linear electromagnetic engine together implement a two-phase cycle in which the system alternates between strong interaction with water to generate thrust and minimal interaction during recovery motion. This introduces anisotropy not only in space, but in time—defining a new class of propulsion systems.

While aerial and underwater environments differ significantly in density and compressibility, both systems converge on a shared governing idea:

Efficient propulsion is achieved not through continuous interaction, but through **asymmetric, phase-structured coupling with the medium**.

The N5Prop system should therefore be understood not as an isolated marine innovation, but as part of a broader propulsion architecture scalable across domains.

Executive Summary

Modern warfare operates across four physical domains—land, air, outer space, and ocean—with increasing emphasis on autonomous systems. Undersea warfare, in particular, is undergoing rapid transformation as surface vessels become more vulnerable to aerial and underwater threats. This shift necessitates the development of highly maneuverable, energy-efficient, and stealth-capable Unmanned Underwater Vehicles (UUVs).

This proposal introduces N5Prop, a propulsion system based on a **linear-stroke electromagnetic engine coupled with an anisotropic propeller**, designed specifically to meet the operational requirements outlined by the Office of Naval Research (ONR).

Unlike conventional rotating propellers, which continuously churn and spin water—wasting a significant portion of input energy—N5Prop operates through discrete propulsion cycles. During each cycle, the propeller engages the water to generate thrust and then returns with minimal resistance. This phase-structured interaction significantly improves energy efficiency, reduces acoustic signature, and enhances maneuverability.

The system is expected to enable long-range operation, rapid directional response, low wake detectability, and high cruising speeds, making it highly suitable for next-generation UUV applications.

Operational Need: Undersea Warfare Context

The modern naval battlespace increasingly favors stealth, autonomy, and rapid maneuverability. Traditional surface ships are vulnerable to detection and attack, while undersea systems offer strategic advantages in concealment and persistence.

UUVs are emerging as critical assets for reconnaissance, interception, and tactical engagement. However, their effectiveness is constrained by propulsion limitations, including energy inefficiency, acoustic noise, and restricted maneuverability.

Current propulsion systems, primarily based on rotating propellers, inherently waste energy through rotational flow components and generate detectable vortex wakes and acoustic signatures. These limitations reduce mission duration and increase vulnerability.

The N5Prop system addresses these challenges by redefining how propulsion interacts with water, focusing on efficient momentum transfer, reduced noise, and rapid response capabilities.

Concept Overview: Linear-Stroke Anisotropic Propulsion

The N5Prop propulsion system is based on a fundamentally different way of interacting with a fluid medium—one that departs from the long-established reliance on continuous rotational motion. At its core, the system replaces persistent, uniform interaction with a **structured sequence of asymmetric interactions**, in which propulsion is generated through controlled, directional engagement with the surrounding water.

In conventional propulsion systems, rotating blades continuously move through the fluid, simultaneously advancing forward and pushing water backward. These two actions occur at the same time and within the same mechanical motion, forcing the system to constantly overcome resistance even as it attempts to generate thrust. This coupling of opposing effects leads to inherent inefficiencies, as energy is expended not only in producing useful forward momentum but also in sustaining the motion required to maintain rotation.

The N5Prop system resolves this inefficiency by separating these functions both physically and temporally. Instead of rotating, the propulsion mechanism operates through a **linear stroke**, driven by an electromagnetic engine that produces direct back-and-forth motion. This linear motion is not merely a mechanical substitution for rotation; it enables a different mode of interaction with the fluid—one in which the system alternates between distinct operational states optimized for different objectives.

During the propulsion phase, the anisotropic propeller transitions into a configuration that maximizes its coupling with the water. In this state, the propeller behaves as a high-resistance surface, effectively engaging a coherent volume of fluid and accelerating it backward. This action is analogous to a tire gripping a solid surface: rather than slipping or dispersing energy into turbulence, the system establishes a firm interaction with the medium and transfers momentum efficiently in a single, directed impulse.

During the reset phase, the propeller undergoes a structural transformation that minimizes its interaction with the fluid. It opens or reconfigures in such a way that resistance is significantly reduced as it returns to its starting position. Because this phase is designed specifically to avoid energy loss, the system expends only a small fraction of the energy required for the propulsion phase. The result is a cycle in which useful work is concentrated in one direction, while losses in the opposite direction are minimized.

This alternating behavior introduces **anisotropy in both space and time**. Spatial anisotropy arises from the directional design of the propeller, which interacts differently with the fluid depending on its configuration. Temporal anisotropy arises from the sequencing of propulsion and reset phases, which ensures that the system is strongly coupled to the fluid only when generating thrust and weakly coupled when recovering.

An intuitive way to understand this mechanism is to consider the difference between continuously stirring water and pushing it in discrete, directed pulses. In the former case, much of the energy is dissipated into swirling motion that does not contribute to forward movement. In the latter, energy is delivered in concentrated bursts that produce clear, directional displacement. The N5Prop system operates according to the second model, emphasizing **coherent momentum transfer over continuous agitation**.

This conceptual shift—from continuous interaction to phase-structured engagement—has important implications for efficiency and control. Because the system is not bound to a fixed rotational cycle, the timing, amplitude, and frequency of each stroke can be adjusted dynamically. This allows the propulsion process to be tuned to specific operating conditions, such as changes in water density, mission profile, or desired speed. It also enables rapid transitions between operational states, supporting both steady cruising and highly responsive maneuvering.

In this sense, the N5Prop system is not simply a new type of propeller or engine, but a redefinition of propulsion as a **controlled sequence of interactions with a physical medium**. By decoupling the mechanisms of thrust generation and motion recovery, and by introducing anisotropy as a central design principle, the system establishes a framework that can be extended beyond underwater applications to other domains where efficient movement through a fluid is required.

To fully understand how this behavior translates into measurable performance gains, it is necessary to examine the underlying physical mechanisms in greater detail. In particular, the role of anisotropy—both in the geometry of the propeller and in the temporal structure of the propulsion cycle—provides the foundation for the efficiency and control characteristics described above. The following section develops this principle and connects it directly to the observed and expected performance of the N5Prop system.

Physical Principle: Anisotropy and Phase-Structured Interaction

At the foundation of the N5Prop propulsion system lies a shift in how propulsion is understood at the physical level. Rather than treating thrust generation as a continuous mechanical process, the system is based on the idea that interaction with a fluid medium can be **structured, directional, and selectively applied in time**. This approach introduces a dual form of anisotropy—spatial and temporal—that governs how energy is transferred from the propulsion system to the surrounding water.

Anisotropy, in its most general sense, refers to directional dependence of physical interaction. In fluid environments, this means that the resistance and momentum transfer associated with motion can vary depending on the direction and configuration of the interacting surface. Natural systems provide clear examples of this principle. Fish, for instance, achieve efficient locomotion not through brute force, but through subtle, directionally structured interactions between their bodies and the water. The arrangement of scales and surface textures creates a preferential response: movement in one direction produces significantly different fluid interaction than movement in the opposite direction. Even seemingly smooth surfaces, such as shark skin, exhibit microstructural features that enhance this directional asymmetry.

The N5Prop system translates this naturally occurring principle into an engineered form by combining **geometric design with controlled motion sequencing**. The anisotropic propeller is constructed to present different hydrodynamic profiles depending on its configuration within the propulsion cycle. However, spatial anisotropy alone is not sufficient to achieve the observed efficiency gains. The key innovation lies in coupling this spatial asymmetry with **temporal structuring of the propulsion process**.

The propulsion cycle is divided into two distinct phases, each optimized for a specific function. During the propulsion phase, the system is configured to maximize interaction with the fluid. The propeller transitions into a closed or high-resistance state, engaging a coherent volume of water and accelerating it backward. In this phase, the system establishes strong coupling with the medium, ensuring that most of the input energy is transferred into directed momentum.

In contrast, the reset phase is engineered to minimize interaction. The propeller opens or reconfigures into a low-resistance state, allowing it to return to its initial position with minimal opposition from the fluid. Because the system is weakly coupled to the medium during this phase, the energy required for recovery is significantly reduced. The result is a cycle in which energy expenditure is concentrated almost entirely in the direction that produces useful work.

This separation of functions introduces **temporal anisotropy**, meaning that the system's interaction with the fluid is not uniform over time. Instead, it alternates between strong and weak coupling states, each precisely aligned with the intended outcome of that phase. Unlike continuous propulsion systems, where opposing effects—thrust generation and drag—occur simultaneously, the N5Prop system ensures that these effects are isolated and independently optimized.

From a physical perspective, this behavior can be understood as a form of selective momentum transfer. Rather than continuously imparting energy into the fluid in multiple directions, the system delivers momentum in discrete, directed impulses. The fluid response is therefore more coherent, with less energy dissipated into turbulence and rotational motion. This leads to a higher proportion of input energy contributing directly to forward propulsion.

This behavior can be expressed more formally in terms of time-dependent momentum transfer. In conventional propulsion systems, thrust is distributed over time as a relatively smooth function $F(t)$, with energy losses embedded in continuous drag and turbulent flow. In contrast, the N5Prop system concentrates momentum delivery into discrete intervals corresponding to the propulsion phase, while minimizing force during the reset phase.

The net impulse delivered over one full cycle can therefore be represented as:

$$I = \int_0^T F(t)\,dt \quad \approx \quad \int_{\text{propulsion phase}} F_{\text{high}}(t)\,dt \; + \; \int_{\text{reset phase}} F_{\text{low}}(t)\,dt$$

where $F_{\text{high}} \gg F_{\text{low}}$, and the reset phase is specifically engineered such that F_{low}contributes minimally to energy loss. This asymmetry allows the system to maximize useful impulse while minimizing non-productive interaction with the fluid.

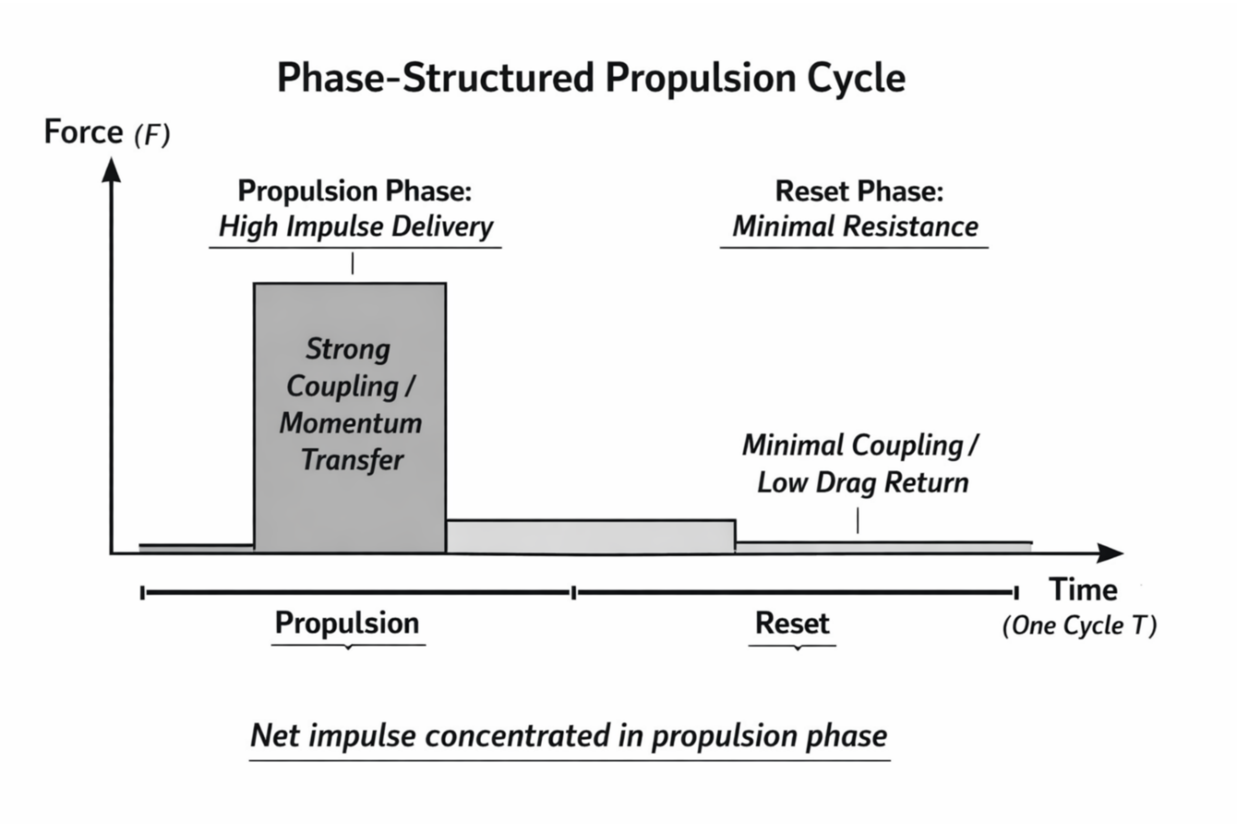

Figure 1. Phase-Structured Propulsion Cycle.
Force applied to the fluid as a function of time over one propulsion cycle. The N5Prop system concentrates momentum transfer during a high-force propulsion phase while minimizing interaction during the reset phase, maximizing useful impulse and reducing energy loss.

An intuitive analogy can be drawn by comparing two methods of moving through water. In one case, continuous stirring produces swirling motion that disperses energy without producing significant net displacement. In the other, discrete pushes generate clear, directional movement. The N5Prop system operates according to the latter principle, emphasizing **coherent, phase-aligned interaction over continuous agitation**.

The implications of this approach extend beyond efficiency. Because the propulsion process is structured in time, it becomes inherently controllable. The strength, duration, and frequency of each phase can be adjusted in real time, allowing the system to respond dynamically to changing conditions or operational requirements. This introduces a level of adaptability that is difficult to achieve in systems constrained by continuous rotational motion.

The combination of spatial and temporal anisotropy thus transforms propulsion into a **designed interaction process**, where performance is determined not only by how much energy is applied, but by how precisely that energy is coupled to the medium. Efficiency, maneuverability, and stealth all emerge as natural consequences of this structured interaction.

While these principles can be expressed in abstract physical terms, their practical realization depends on the ability to generate and control the required motion with precision and reliability. The effectiveness of phase-structured, anisotropic propulsion therefore rests on how these concepts are embodied in a physical system capable of operating under real-world conditions.

The following section describes how these principles are translated into the architecture of the N5Prop system, where electromagnetic actuation, structural design, and material selection are integrated to produce the controlled motion and fluid interaction described above.

System Architecture

The N5Prop propulsion system is built as an integrated electromechanical platform in which each component is designed to support the central principle of phase-structured, anisotropic interaction with the fluid medium. Rather than treating the engine and propeller as separate subsystems connected through mechanical transmission, the architecture is conceived as a unified system in which energy generation, control, and fluid interaction are tightly coordinated.

At the core of the system is a linear electromagnetic engine. Unlike traditional propulsion systems that rely on rotary motors and require additional mechanical assemblies to convert rotational motion into linear thrust, the N5Prop engine generates linear motion directly through electromagnetic interaction. This eliminates an entire class of mechanical inefficiencies associated with shafts, gears, and bearings, and significantly reduces energy losses due to friction and vibration. The reduced number of moving parts also enhances reliability and simplifies maintenance, which is particularly important for autonomous underwater systems operating over extended periods.

Equally important is the precision of control enabled by the electromagnetic nature of the engine. Because motion is governed directly by electrical input rather than mechanical inertia, the system can respond instantaneously to control signals. This allows fine modulation of stroke length, frequency, and timing, enabling the propulsion cycle to be dynamically adjusted to mission requirements or environmental conditions.

The anisotropic propeller constitutes the second critical element of the architecture. Constructed from ultra-light composite materials with high tensile strength, the propeller is designed to exhibit dramatically different hydrodynamic behavior depending on its state within the propulsion cycle. During the propulsion phase, the propeller closes and presents a high-resistance surface to the water, effectively “grabbing” a coherent volume of fluid and accelerating it backward. During the reset phase, it opens to minimize resistance as it returns to its initial position. This directional asymmetry is the physical mechanism that enables efficient phase separation between thrust generation and recovery.

Material selection plays a central role in enabling this behavior. The engine components rely on ferromagnetic materials optimized for rapid electromagnetic response, while the propeller elements require a combination of low mass, structural resilience, and fatigue resistance under rapidly alternating loads. Together, these material choices allow the system to sustain high-frequency operation without degradation, supporting both performance and durability.

The resulting architecture is not simply a combination of known components, but a coordinated system in which electromagnetic control, mechanical motion, and fluid interaction are aligned around a single operational principle. This integration is what enables the N5Prop system to achieve performance characteristics that are difficult or impossible to realize within conventional propulsion frameworks.

Performance Advantages

The performance characteristics of the N5Prop system emerge directly from its underlying physical principle of phase-structured interaction with the fluid medium. By separating propulsion into distinct phases and minimizing energy loss during non-productive motion, the system achieves a level of efficiency and responsiveness that departs significantly from traditional designs.

Energy efficiency is perhaps the most immediate and consequential advantage. In conventional rotating propellers, a substantial portion of input energy is expended in continuously accelerating water in directions that do not contribute directly to forward motion, particularly through rotational and turbulent flow components. In contrast, the N5Prop system concentrates energy delivery into discrete propulsion phases, during which water is accelerated primarily in the desired direction. Because the reset phase is engineered to minimize resistance, very little energy is wasted in preparing for the next stroke. This leads to a higher proportion of input energy being converted into useful thrust, directly extending operational range and mission duration.

The acoustic signature of the propulsion system is also fundamentally altered. Rotating propellers generate continuous broadband noise due to blade passage, cavitation, and turbulent wake formation. The linear-stroke operation of N5Prop produces a markedly different acoustic profile, characterized by lower-frequency, lower-amplitude emissions. The absence of continuous rotational turbulence reduces the likelihood of detection by sonar systems, enhancing the stealth capabilities of the UUV.

Wake characteristics further contribute to stealth and operational effectiveness. Conventional propellers generate expanding vortex structures driven by rotational flow, which can persist and be detected over significant distances. The N5Prop system, by contrast, produces narrow, directionally focused water displacement with minimal rotational components. The resulting wake is weaker, more localized, and dissipates more rapidly, reducing the vehicle's hydrodynamic footprint.

Responsiveness and maneuverability are enhanced by the elimination of rotational inertia. In traditional systems, spinning components resist rapid changes in speed and direction due to angular momentum. The linear electromagnetic engine of the N5Prop system has no such constraint, allowing the propulsion cycle to be halted, reversed, or modulated almost instantaneously. This enables rapid acceleration, deceleration, and directional changes, which are critical in both evasive maneuvers and precision navigation.

The system's capability for high-speed operation complements these advantages. By enabling efficient transfer of energy into forward motion and allowing rapid modulation of thrust, the N5Prop system supports short bursts of high cruising speed, on the order of 100 km/h. This capability is particularly relevant for interception and pursuit scenarios, where both speed and responsiveness determine mission success.

Taken together, these performance characteristics define a propulsion system that is not only more efficient, but also more adaptable and tactically versatile than conventional alternatives.

Comparative Analysis: Linear vs Rotational Propulsion

The distinction between linear-stroke anisotropic propulsion and conventional rotational propulsion is not merely a matter of mechanical configuration; it reflects a deeper difference in how each system interacts with the fluid medium to generate thrust.

In rotating propulsion systems, thrust is produced through continuous blade motion that simultaneously performs two functions: advancing through the fluid and accelerating it backward. Each blade must move forward against the resistance of the water before it can contribute to propulsion. This results in a persistent drag component that is intrinsic to the operation of the system. Additionally, the rotation of the propeller imparts angular momentum to the water, creating swirling flows and turbulence that do not contribute to forward motion. These effects represent a fundamental inefficiency, as energy is continuously expended in ways that do not directly produce thrust.

The apparent smoothness and continuity of propeller rotation can obscure these losses, but from a physical standpoint, the system is constantly working against itself—expending energy to overcome drag while simultaneously attempting to generate forward momentum.

The N5Prop system, by contrast, separates these functions in time. During the propulsion phase, the system is optimized for maximum coupling with the fluid, delivering momentum efficiently in the desired direction. During the reset phase, the system is configured to minimize interaction with the fluid, reducing drag to a fraction of that experienced during propulsion. This temporal separation eliminates the need to perform opposing actions simultaneously and allows each phase to be optimized independently.

The result is a propulsion mechanism in which energy is used more selectively and effectively. Rather than continuously fighting drag and turbulence, the system avoids them during non-productive phases and concentrates effort only where it yields useful work.

This distinction becomes particularly significant in autonomous systems, where energy availability is limited and efficiency directly impacts mission capability. By reducing wasted energy and improving thrust efficiency, linear-stroke anisotropic propulsion offers a fundamentally more effective approach for UUV applications.

Naval Relevance and Use Cases

The operational characteristics of the N5Prop system align closely with the evolving requirements of modern naval operations, particularly in the context of unmanned and autonomous systems. As undersea warfare becomes increasingly central to strategic planning, propulsion technologies must support not only performance, but also survivability, stealth, and adaptability.

For reconnaissance missions, where prolonged operation and low detectability are paramount, the energy efficiency and reduced acoustic signature of the N5Prop system provide clear advantages. Extended mission duration allows UUVs to operate deeper within contested environments, while low noise and minimal wake reduce the risk of detection.

In interception and pursuit scenarios, the system's rapid response capabilities become critical. The ability to accelerate quickly, change direction with minimal delay, and achieve high short-term speeds enables UUVs to engage moving targets or evade threats effectively. These capabilities are difficult to achieve with traditional propulsion systems constrained by rotational inertia.

The system is also well-suited for distributed and swarm-based operations. Smaller UUVs equipped with efficient, low-noise propulsion can operate cooperatively over large areas, performing coordinated tasks such as surveillance, mapping, or defense. The scalability of the N5Prop concept supports such applications, as the underlying principle does not depend on vehicle size.

Beyond UUVs, the technology has potential applications in larger platforms, including submarines and surface vessels. While scaling introduces additional engineering challenges, the fundamental advantages—efficiency, reduced noise, and improved maneuverability—remain relevant. With sufficient development, the principles demonstrated in N5Prop could influence a broader range of naval propulsion systems.

Conclusion: Toward a Phase-Structured Propulsion Future

The N5Prop system represents a departure from the long-standing paradigm of continuous rotational propulsion. By introducing phase-structured interaction with the fluid medium and leveraging anisotropic design principles, it offers a fundamentally different approach to generating thrust—one that prioritizes efficiency, control, and adaptability.

This shift has implications that extend beyond a single class of underwater vehicles. It suggests a broader rethinking of propulsion systems as dynamic interaction processes, where performance is determined not only by mechanical power, but by how and when that power is applied to the surrounding medium.

The path forward involves several parallel efforts. Experimental validation of the propulsion concept will be essential to quantify performance gains and refine system parameters. Computational modeling, including fluid dynamics and electromagnetic simulations, will support optimization and scaling. Material development will play a critical role in ensuring durability and performance under high-frequency operation. Finally, integration with control systems and autonomous navigation frameworks will enable the full realization of the system's capabilities in real-world applications.

As these efforts progress, the N5Prop system can serve as a foundation for a new class of propulsion technologies applicable across domains. The same principles that enable efficient underwater propulsion may be adapted to aerial systems, hybrid environments, and future platforms that operate at the boundaries between them.

In this sense, N5Prop is not only a solution to a specific engineering problem, but an entry point into a broader technological transition. It opens the possibility of designing propulsion systems that are not constrained by legacy approaches, but are instead guided by a deeper understanding of how structured interaction with physical media can be harnessed to achieve superior performance.

The transition from continuous to phase-structured propulsion may ultimately prove to be as significant as the transition from mechanical to electromagnetic systems—marking the beginning of a new era in how motion through fluid environments is conceived and achieved.