MARINE PROPULSION SYSTEM USING
LINEAR-STROKE ENGINE AND ANISOTROPIC PROPELLER

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EXECUTIVE SUMMARY

Given four physical battlefields in the warfare of today – land, outer space, air, and ocean – and the increasing vulnerability of surface ships to aerial and undersea attacks, development of highly maneuverable long-distance undersea drones (UUVs) becomes imperative since UUVs play an important role in modern undersea warfare. Responding to the Office Naval Research (ONR) position on general specifications of the UUV propulsion systems[1], we propose an efficient propulsion system using a linear-stroke engine and an anisotropic propeller (henceforth , the system is referred to as N5Prop).

Consequently, we propose to develop and test an energy efficient and rapid-response propulsion system for US Navy unmanned undersea vehicles (UUV).

1. WHY LINEAR-STROKE ANISOTROPIC PROPELLER?

Energy Efficiency

Conventional marine propellers churn and spin water wasting a significant fraction of power delivered to them by the engine. The wasted energy from using this type of conventional propeller in unmanned undersea vehicles (UUV) therefore limits the duration a UUV can actively engage on a mission, reducing the likelihood of success. To overcome this type of wasteful design, N5Digital developed an anisotropic propeller that "grabs" complete packets of water – water bullets – and pushes them directly backward efficiently utilizing the majority of the power on developing propulsion thrust. The N5Digital propellers developed for the UUV propulsion systems act similarly to the car's four rubber tires that grab the road tightly without slippage, push the car backwards, while quickly accelerating the car.

Low-Drag Propeller

Our uniquely designed N5Digital propellers have extremely high directional anisotropy: the drag on the propeller during the idle part of the cycle when it moves forward, in the direction of the UUV's motion is drastically lower than the "useful drag" during the propulsion part of the cycle when the propeller grabs and pushes water backwards. The unique design of the N5Digital propeller using ultra-light materials minimizes the losses due to the propeller's continuous back-and-forth movement.

Efficiency of Linear and Rotating Propellers: A Comparative Analysis

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[1] *"Explore and exploit the lack of underwater propulsion systems that can efficiently work across a wide variety of speeds over long distances. Of particular interest is a propulsion system able to transition between low and high speeds, to include the ability to stop and re-start at any time. The program pursues technologies and systems that support development and demonstration of a system that can propel an underwater vehicle in the ways listed.*

Deployed unmanned undersea systems require higher and higher levels of endurance and maneuverability as they execute their missions. The Echidna Innovative Naval Prototype (INP) program has several lines of effort, one of which focuses on power and propulsion. Another thrust focuses on Materials Science, and so consideration of materials used is important. ONR is looking for innovative designs and concepts to enable extremely long-duration missions through efficient use of the available power."

The conventional rotating propellers develop continuous drag during their operation that further reduces their efficiency. The origin of that drag is a continuous advancement forward of each propeller blade forward that produces significant drag that reduces useful thrust and decreases efficiency. Note that this constantly present drag remains camouflaged by the seemingly effortless propeller rotation, although each blade must advance forward while overcoming friction and dynamic resistance of the water (drag) to be able to subsequently push water backwards to generate propulsion. We will include a quantitative analysis based on experiments in the present proposal. The results will allow us to estimate and compare the efficiency of conventional rotating and our linear anisotropic propellers.

2. OBJECTIVE

Develop and test an energy efficient and rapid-response propulsion system for US Navy unmanned undersea vehicles (UUV).

3. BACKGROUND

Undersea Warfare

Given four physical battlefields in the warfare of today – land, outer space, air, and ocean – and the increasing vulnerability of surface ships to aerial and undersea attacks, development of highly maneuverable long-distance undersea drones (UUVs) becomes imperative since UUVs play an important role in modern undersea warfare. Responding to the Office Naval Research (ONR) position on general specifications of the UUV propulsion systems mentioned earlier, we propose an efficient propulsion system using a linear-stroke engine and an anisotropic propeller, N5Prop.

N5Didital UUV Concept

The N5Prop linear propulsion system proposed here is a part of a wider N5Digital program developing a new concept of an Unmanned Underwater Vehicle. Although a detailed discussion of this N5Digital UUV program is outside of the scope of the present proposal focusing on propulsion only, below are its key conceptual features:

- No-propeller, body-vibration-based anisotropic propulsion.
- Smart materials for the anisotropic body shell.
- Non-rigid frame infrastructure.
- Vertical plane orientation.
- Internal-wave propagation through water.
- Low power demand and high efficiency allowing long range autonomous travel.
- Low wake and low noise hardening sonic detection.
- Miniature size appropriate for low payload applications.

Anisotropy in Underwater Propulsion

Anisotropy is the key element in vibration-based propulsion in water. Fish can swim extremely fast and efficiently because any, even minute gross body movements and even vibrations, create a preferential, forward momentum. This happens because of the natural anisotropy of the texture of their skin surface and their entire bodies covered by the scales arranged in a unidirectional, anisotropic pattern, so their entire bodies become natural propulsion engines. Note that the seemingly smooth skin of the sharks also has a strongly expressed directional anisotropy.

4. N5PROP: LINEAR-STROKE ANISOTROPIC PROPELLER PROPULSION SYSTEM

SPECIAL N5PROP CAPABILITIES FOR UNDERWATER OPERATION

Based on the general technical specifications of the Office of Naval Research, below we discuss the Linear-Stroke Anisotropic Propeller Propulsion system (N5Prop) focusing on the UUV's operating and design features critical for different autonomous and controlled underwater combat and training scenarios.

— **Minimal Sonar and Vortex-Wake Detection**

Low frequency, low noise footprint produced by the N5Prop's linear-stroke electric engine, and its linear anisotropic propeller reduces the possibility of sonar detection. Underwater vehicles using the N5Prop system are expected to produce extremely low-profile vortex wakes since their linear propellers create narrow columns of water, with no rotational component as propellant. In contrast, conventional rotating propellers cause radial expansion of the wake due to centrifugal forces acting on the water jets. Importantly, the linear propulsion system leaves the vortex wakes significantly weaker than those left by conventional rotating-propeller marine propulsion systems.

Development of vortex-based inversion methods for submarine detection will be directly applicable to detection of UUVs. Note that the vortex dissipation will be slower when UUV propagation in linearly stratified waters, so minimizing intensity of vortices is an important objective of their designers.

— **Ability to Rapidly Stop and Start**

Quick stops can be executed by an instant stop of the linear propeller. No inertia typical for conventional propellers exists. The N5Prop system allows a 100 ms direction reversal. High acceleration experienced at the moment of direction reversal is not important for unmanned vehicles.

— **Ability To Rapidly Decelerate and Accelerate**

Linear propulsion engine has low inertia and can instantaneously change its speed and thrust allowing for quick acceleration and deceleration of the underwater drone.

— **High Maneuverability**

Linear movement of the engine parts allows enhanced maneuverability of the underwater drone because of the lack of gyroscopic effects present in the engines based on parts rotating at high speeds. The gyroscopic effect may be more pronounced in smaller and lighter underwater vehicles such as drones.

— **Efficient Long-Distance Performance**

A relatively small number of moving parts in the N5Prop system maximizes energy efficiency and economic use of electric energy over long travel distances. In addition, its design allows a quick and fine control of the UUV's speed, adding to its strategic, long distance and tactical engagement maneuverability.

— **High Cruising Speed**

The UUV design driven by the N5Prop system is intended to allow achieving a cruising speed of 100 km/h over a short period of time. High speed and acceleration are critical for UUVs in interception and pursuit combat scenarios.

MAIN DESIGN CHARACTERISTICS

The unique N5Digital propulsion technology is based on two key elements: (1) an electrical linear-stroke engine using special ferromagnetic materials and (2) a unique anisotropic propeller made of ultra-light composite materials. The propeller is designed to minimize the loss of momentum during its forward stroke phase (completely open) while effectively delivering forward momentum to the UUV while moving in opposite direction (completely shut).

Linear-Stroke Engine
Linear motors have advantages over traditional motors since there are fewer moving parts and lower loss of energy to friction or vibrations. No need for mechanical parts to convert the engine's rotational motion into linear thrust applied to the propeller saves energy. Since the operation of a linear motor is purely through electromagnetism, full control is instantaneous and precise.

Anisotropic Propeller
Conventional marine propellers churn and spin water wasting a significant fraction of power provided by the engines. In contrast, the N5Prop's propeller "grabs" complete packets of water and pushes them backward thus utilizing most of the power of the linear propulsion electric engine with no energy wasted on churning and spinning the water. As a result, while the conventional propeller churns and spins water, our propeller grabs water tightly, like the car wheels grab the road, and immediately pushes it directly backwards, quickly accelerating the UUV. The N5Digital propeller design is "patent-pending".

Special Materials
The core element of the electrical engine uses light material with high "ferromagnetic" properties. The anisotropic propellers will be constructed of light composite materials with high tensile strength. The above two specific characteristics are crucial for reducing UUV's weight and accommodate the rapid and high load variations during abrupt acceleration regimes.

FUTURE NAVAL RELEVANCE
Conventional marine engines spend a substantial part of their power to spin the water jet generated by a rotating propeller while providing linear propulsion. The energy spent on rotating that water is a waste since it does not contribute to the boat propulsion. The N5Prop propulsion system technology with enough R&D being that it is a new concept, will provide long distance efficiency, unbelievable maneuverability, and vibration and noise reduction. Successful development of the UUV N5Prop propulsion system will allow scaling up its main features to surface ships and submarines.

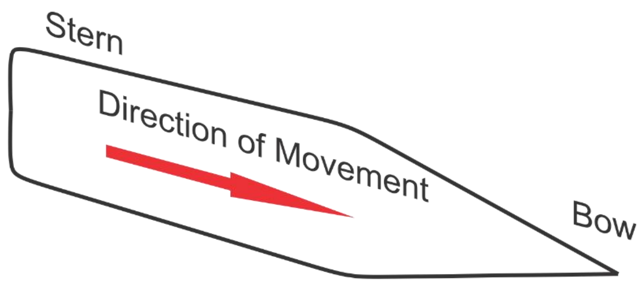
5. OPERATIONAL NAVAL CONCEPT
Our objective is to design a highly maneuverable, low-profile UUV with a long-range propulsion system for underwater navy combat and training applications. The concept is to start with a clear understanding of available resources and field cases. Followed by design drafting and simulation using tools such as Computational Fluid Dynamics and Computational Electromagnetic Modeling to design an appropriate linear electromagnetic motor. The calculations at different cases will be clearly documented and allow for an appropriate demonstration and testing to gather additional empirical data.

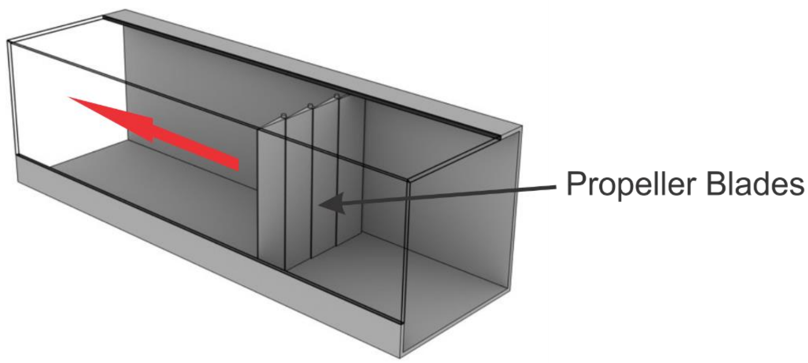
6. PROOF-OF-CONCEPT: DESIGN AND DEMONSTRATION

LINEAR-STROKE PROPULSION CYCLE

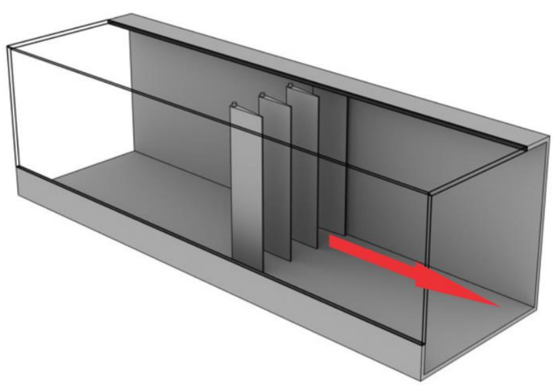
Each cycle of the engine/propeller stroke has two phases - Propulsion Phase and Reset Phase - as illustrated below. The fully closed position of the propeller blades corresponds to the propulsion phase of the linear stroke when the propeller moves away from the boat providing propulsion.

The fully open position of the blades corresponds to the reset phase, when the propeller returns to its starting location closest to the boat’s bow; the key feature in this phase is that during reset, the propeller encounters minimal water resistance, that is significantly lower that that during the propulsion phase, thus, “anisotropic” propeller. The schematics on Fig. 1 illustrate two phases of the linear-stroke engine-propeller propulsion cycle.





PROPELLER PROPULSION PHASE: Propeller moves towards stern



PROPELLER RESET PHASE: Propeller moves towards bow

Fig. 1. N5Digital Anisotropic Propeller: Propulsion and Reset Phases

As the N5Prop system goes through its cycles in a water pool environment, measurements will be taken of various parameters, such as water displacement, power consumption, thrust, and acceleration (free-floating model test). These data will allow to evaluate the mechanical and propulsion performance of the N5Prop system and validate the results generated in associated computer simulations.

SCOPE OF WORK

To illustrate the principle and operational effectiveness of the linear-stroke engine with anisotropic propeller, we plan to assemble and test the prototype of our propulsion system in a specially designed testing water vessel. The scope of work to design and test the prototype of the N5Prop propulsion system is presented below.

1. **Design the N5Prop prototype with the following components**
   1.1. Linear-stroke electromagnetic engine (3 mo),
   1.2. Anisotropic propeller (3 mo),
   1.3. Controllable power supply (1 mo),
   1.4. Vessel for testing performance of the prototype (0.5 mo),
   1.5. Control system (2 mo),
   1.6. Thrust measurement equipment (1 mo),
   1.7. Data collection, storage, and processing system (1.5 mo).
   1.8. Prepare Status report describing N5Prop system design.
2. **Assemble and test key elements of the N5Prop prototype**
   2.1. Linear electromagnetic engine (4 mo),
   2.2. Anisotropic propeller (3 mo),
   2.3. Controllable power supply (2 mo),
   2.4. Vessel (6'x6'x4') for testing performance of the prototype of the N5Prop system in water (1 mo),
   2.5. Engine and propeller control system (2 mo).
   2.6. Prepare Status report describing assembly of N5Prop system.
3. **Test the prototype N5Prop system**
   3.1. Develop testing program including measurement procedures and data collection (1 mo),
   3.2. Develop data analysis plan (1 mo),
   3.3. Assemble the prototype of the N5Prop propulsion system, install it in the test vessel and conduct a test run (3 mo),
   3.4. Create the final version of the prototype of the N5Prop system and conduct the final test run (2 mo),
   3.5. Conduct the experiments measuring performance parameters (2 mo):
   - Water jet parameters (e.g., speed, shape, wake dissipation),
   - Electric power consumption,
   - Developed thrust as a function of engine rate,
   - Acceleration (free-floating model),
   - Noise level at different engine rates.

   3.6. Process and analyze obtained data (2 mo),
   3.7. Prepare the final project report describing N5Prop test results (1 mo).