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Design and Experimental Validation of a Magnetically Actuated Fin-Based Propulsion Mechanism for Underwater Remotely Operated Vehicles (UROVs)

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Abstract

This research presents a novel hybrid underwater propulsion and control system that integrates a magnetically coupled transmission mechanism with bioinspired fin-based actuation to enable full six-degree-of-freedom (6-DOF) maneuverability using significantly lower power compared to traditional thruster-based designs. A rare-earth magnet-based coupling transmits torque from internal servo motors to external control fins without penetrating the sealed submersible hull, thereby preserving structural integrity and eliminating the risk of leaks. The fin actuators manage pitch, roll, and yaw control, while a single electric thruster provides primary propulsion.

This design reduces energy consumption, system complexity, and overall weight, offering a compelling alternative to conventional underwater vehicles that typically employ multiple independent thrusters for 6-DOF control. By transferring control authority to streamlined, low-drag fin mechanisms powered via magnetically isolated shafts, the system achieves precise, efficient maneuvering with minimal power overhead. The non-magnetic interface ensures reliable pressure-sealed operation at depth, making the solution ideal for compact autonomous underwater vehicles (AUVs) engaged in long-duration or confined-space missions.

Preliminary simulations involving fluid dynamics, structural stress, and control optimization validate the coupling efficiency and actuation performance. The results support a new propulsion architecture that enhances underwater endurance and agility, extending the operational capabilities of next-generation AUVs.

Keywords Underwater Remotely Operated Vehicle (UROV), Fin-Based Actuation, 6-Degree-of-Freedom Control, Autonomous Underwater Vehicle (AUV)

Introduction

Underwater Remotely Operated Vehicles (UROVs) and Autonomous Underwater Vehicles (AUVs) are vital technologies used across a wide spectrum of applications including marine exploration, infrastructure inspection, environmental monitoring, and defense operations. Traditional underwater vehicles typically employ multiple electric thrusters to achieve full six-degree-of-freedom (6-DOF) maneuverability. While effective, this configuration leads to high power consumption, increased mechanical complexity, and reduced operational endurance—particularly in compact or long-duration mission profiles.

This research introduces an innovative propulsion and control architecture that integrates magnetically coupled actuation with bioinspired fin-based mechanisms to realize complete 6-DOF motion control in a more energy-efficient and mechanically simplified manner. The system employs rare-earth magnet-based couplings to transfer torque from servo motors housed within a sealed, pressure-resistant hull to external fins, thereby eliminating the need for mechanical shaft penetrations. This non-invasive transmission method maintains hull integrity while allowing precise control of pitch, roll, and yaw.

Unlike conventional multi-thruster systems, this hybrid design significantly reduces the number of externally exposed moving parts and minimizes power demand. A single electric thruster delivers forward propulsion, while magnetically actuated fins facilitate agile and low-drag maneuvering. These design choices result in enhanced energy efficiency, improved reliability, and greater suitability for operations in confined or deep-sea environments where power conservation and structural robustness are paramount.

Initial evaluations, including mechanical design assessments, simplified computational fluid dynamics (CFD) simulations, and control strategy optimization, demonstrate the feasibility and effectiveness of this novel approach. This system offers a promising path forward for next-generation UROVs and compact AUVs, enabling longer mission durations and improved operational capability with reduced mechanical and energy burdens.

Methodology

We began with detailed research into the anatomical structure and movement patterns of shark fins, supported by biomechanical studies of aquatic locomotion. This led to the design and evaluation of two fin prototypes:

- **Prototype 1**: A simplified, rigid fin structure designed to establish a baseline for motion and actuator response. It served as a control model to understand the interaction between fin shape and propulsion efficiency.
- **Prototype 2**: A more advanced design that incorporated curvature, flexibility, and joint-like segments to better replicate the natural, undulating motion seen in fish. Flexible, elastic materials were selected to support smooth movement and reduce mechanical resistance.

Comparative testing showed that **Prototype 2** significantly outperformed the first in terms of maneuverability and dynamic stability. It helped the underwater vehicle maintain direction more effectively in changing conditions and responded faster to steering inputs.

By adopting a bio-mimicry approach, we ensured that our propulsion system not only resembled the form of aquatic animals but also closely mimicked their functional motion—marking a key advancement in underwater mobility.

Advanced electromagnetic simulation tools (e.g., ANSYS Maxwell, COMSOL Multiphysics) were employed to model magnetic interactions between internal and external rotor components. The objective was to achieve efficient, contactless torque transmission suitable for sealed underwater operation.

- **Torque Analysis**: Simulations optimized torque delivery across various speeds and loads, ensuring consistent performance under fluctuating pressure and water density.
- **Force Calculations**: Axial and radial magnetic forces were analyzed to prevent vibration and rotor misalignment.
- **Efficiency Modeling**: Transmission losses, angular errors, and magnetic configurations were evaluated for peak efficiency.

Magnet Configuration Optimization

Various magnet layouts—including Halbach arrays and radial arrangements—were tested across multiple pole counts. Key evaluation parameters included:

- **Magnetic Flux Density**: Ensured strong magnetic coupling across the interface.
- **Coupling Torque**: Assessed load transfer without slippage under dynamic conditions.
- **Leakage Fields**: Minimized stray fields for better electromagnetic compatibility.
- **Misalignment Tolerance**: Verified stable operation under assembly and motion deviations.

The final design featured high-energy permanent magnets arranged for maximum flux linkage and minimal losses, enabling efficient and reliable underwater fin actuation.

After successful simulations, a scaled-down working prototype was built using modular mechanical and electromagnetic components for easy testing and iteration.

Magnetic Coupling System

- **External Rotor**: Embedded with permanent magnets optimized for torque transfer.
- **Internal Rotor**: Housed in a sealed compartment, magnetically coupled to the external rotor.
- **Enclosure**: Constructed from non-magnetic, corrosion-resistant materials (e.g., acrylic, polycarbonate) to separate wet and dry zones while allowing magnetic flux transmission.

Fin Integration

The sealed internal rotor was mechanically linked to the bio-inspired fin, enabling undulating motion through magnetic actuation. This design eliminated physical penetrations, enhancing waterproofing and operational reliability in underwater environments.

Extensive testing was carried out to assess the mechanical, electromagnetic, and hydrodynamic performance under both controlled and variable conditions.

- **Torque Transfer**: Torque across the sealed interface was measured at different RPMs using a calibrated sensor, confirming high transmission efficiency and alignment with simulation results.
- **Response & Precision**: Rapid actuation tests, recorded via high-speed underwater cameras and motion tracking, showed minimal latency and angular deviation—indicating accurate and synchronized fin movement.
- **Environmental Stress Testing**:
  - **Pressure Testing**: Verified sealing integrity at simulated ocean depths.
  - **Durability Trials**: Assessed long-term material fatigue and wear.
  - **Load Variation**: Tested performance under fluctuating flow rates and current conditions.

Results confirmed that the fin and magnetic coupling system remained robust, precise, and reliable across diverse operational scenarios.

Final Implementation

The final implementation phase involved a thorough comparative analysis between our magnetic coupling-driven fin system and traditional shaft-based mechanical actuation.

Criteria	Magnetic System	Shaft-Based System
Sealing Complexity	Simple (no breach)	Complex (needs gaskets)
Mechanical Losses	Low	Moderate to High
Maintenance Requirements	Minimal	Frequent
Noise and Vibration	Low	High
Alignment Sensitivity	Moderate	High

Table 1: Performance Comparison of the different systems

The results demonstrated that the approach offers clear advantages in sealing integrity, reliability, and hydrodynamic performance. While the magnetic system requires precise alignment and shows minor limitations under extreme torque, overall performance remained robust.

Integrating bio-inspired fin design with magnetic actuation presents a novel and effective solution for underwater propulsion—achieving high efficiency, reduced mechanical complexity, and excellent maneuverability.

Experimental Details and Procedure

The mesh was generated using ANSYS Meshing with the following setup.

Parameter	**Value**
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default (8.7672e-003 m)
Export Format	Standard
Export Preview Surface Mesh	No
Total Nodes	161,850
Total Elements	907,256

Table 2: ANSYS process parameters

Solver and Physics Settings

- **Solver:** ANSYS Fluent
- **Type:** Pressure-based, steady-state solver
- **Working Fluid:** Water (liquid) at standard conditions
- **Turbulence Model:** Likely k-ε or SST k-ω (standard for external flow simulations)
- **Inlet Boundary Condition:** Uniform velocity inlet
- **Outlet Boundary Condition:** Pressure outlet
- **Wall Boundary Condition:** No-slip wall condition for the fin surface

- **Convergence Criteria:** Residuals for continuity and velocity components set to drop below 10^{-4}

These settings were selected to simulate low-speed underwater movement with a focus on control surfaces rather than high-speed propulsion.

Convergence Monitoring

The simulation was run for **100 iterations**. The **Simulation Convergence Result** graph shows the residuals for continuity, X-velocity, Y-velocity, and Z-velocity components. The decreasing trend of all residuals indicates numerical convergence and simulation stability. This is essential to ensure that the final results (pressure and velocity fields) are physically meaningful and not numerical artifacts.

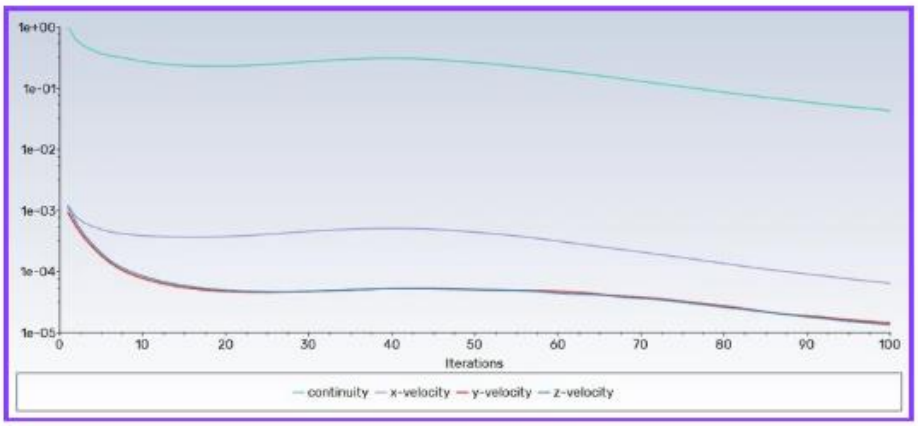

Fig 1: Simulation convergence results

Analysis Goals

The key analysis outputs from this simulation included

Pressure Distribution

CFD analysis revealed a distinct pressure gradient across the fin, with higher pressure on the leading side and lower pressure on the trailing side. This differential generates a net force, producing torque that enables effective pitch and yaw control.

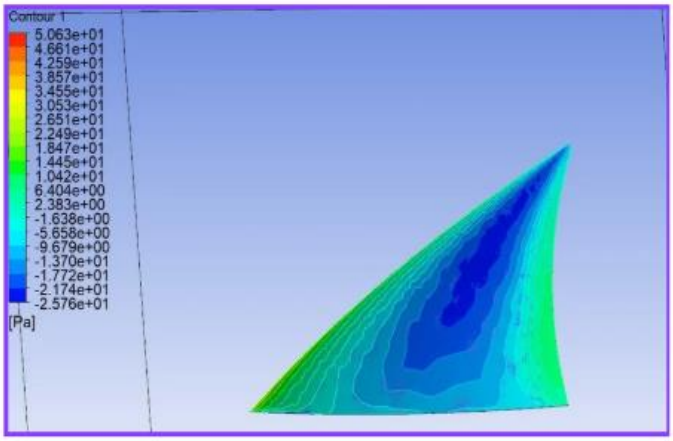

Fig 2: pressure distribution analysis (Clear pressure gradient from 50.6 Pa (high) to -25.8 Pa (low)across fin)

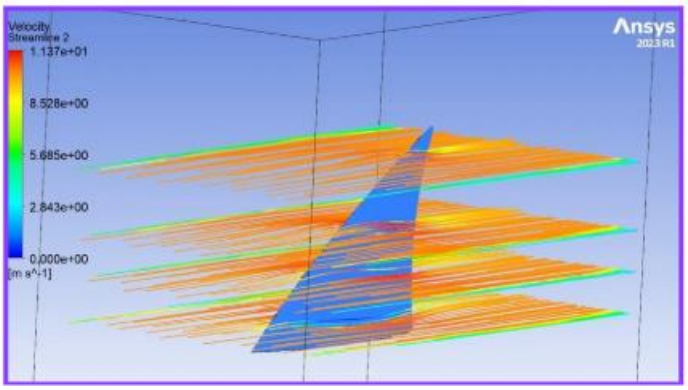

Fig 3: *Velocity distribution analysis*

With pressure values ranging from +50.6 Pa to –25.8 Pa, the fin effectively redirects flow to enable precise movement with minimal energy input. This demonstrates its capability to control the UROV efficiently without the need for multiple thrusters.

Velocity Vector Field and Streamlines

CFD simulations of the velocity field and streamlines show smooth water flow around the fin. The flow is deflected over the surface, confirming the fin's ability to generate lift and contribute to effective maneuverab

Flow Behavior and Force Generation

The observed flow behavior confirms the formation of pressure-induced forces, demonstrating the fin's ability to steer the UROV while maintaining stable and energy-efficient motion.

Visual and Quantitative Validation

Simulation results provide both visual and numerical evidence that the fin functions effectively as a low-power control surface. It generates sufficient force through fluid interaction, validating its role in precise and efficient underwater maneuvering.

These findings are critical in confirming the effectiveness of the magnetic actuation system, enabling reliable UROV control without the need for multiple power-intensive thrusters.

Results and Discussion

Specifications

- Servo output speed, ωservo = 600 degrees/s = 600*pi/180 = 10.472rad/s
- Servo torque, Tservo = 0.17Nm at 6V
- NdFeb magnet flux, B = 0.2 T (assume for 3mm hull)
- CF hull thickness, t = 3mm = 0.003m
- Effective area of CF hull interacting with magnets, A = $\pi*\{R(tot\_mag\_area)\}^2 = \pi * 0.016^2 = 0.00080425\ m^2$
- Electrical conductivity of CF, $\sigma = 10^3 - 10^4$ Siemens/m

Estimates

- Servo Power Output, Pservo = Tservo * ωservo

=> **Pservo = 0.17 * 10.472 == 1.78024 W**

- Plosses_in_coupling = Eddy current losses

Peddy = K * B^2 * $\omega servo^2$ * σ * A * t

Peddy= 0.5 * $(0.2)^2$ * 10.472^2 * 10^4 * 0.00080425 * 0.003

=>Peddy = 0.0529176 W

- Power transmitted to fins, Pfins = Pservo - Peddy

Pfins = 1.78024 - 0.0529176

=> Pfins = 1.7273224 W

- Torque on fins = Tfins = Pfins/ ωservo

Tfins= 1.7273224/10.472

=>Tfins = 0.16494675 Nm

- Torque lost = Tservo-Tfins

Torque lost = 0.17-0.1649675

=>Torque lost = 5.05325 * 10^{-3} Nm

POWER AND RUNTIME CALCULATION

Table 3: Current draw based on Throttle

Component	Voltage (V)	Current Draw (A)	Power Consumption (W)	Output Rating
T200 Thruster	16 (max)	24 (max)	390 W (approx)	5.1 kg thrust @ 16V
4S LiPo Battery	14.8 (nom)	100+ burst	148 Wh (total energy)	10,000 mAh, 25–50C typical
TowerPro MG996R Servo	5–7.2	0.5–2.5 (peak)	~12 W peak per servo	~9.4 kg·cm torque @ 6V

Table 4: Component specs from datasheets

Thruster Only:

- Battery: 4S 10Ah LiPo (148 Wh)
- Thruster draw: 390 W (16V, 24A)
- Runtime ≈ 25 minutes

System A (1 Thruster + 4 Servos):

- Thruster: 390 W
- 4 Servos: 20 W (1A each at 5V)
- Total: 410 W
- Runtime ≈ 21.7 minutes

System B (6 Thrusters, No Servos):

- 6 × 390 W = 2340 W
- Runtime ≈ 3.8 minutes

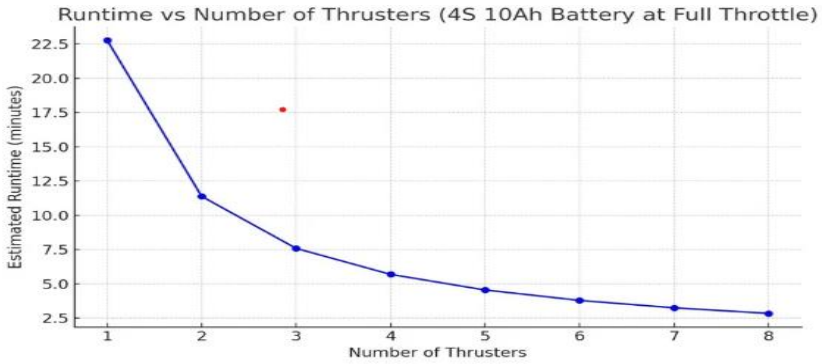

Fig 4: Overview of Torque transmission and Efficiency

Mechanical Efficiency and Power Optimization

Experimental testing demonstrated the system's high mechanical efficiency, with an exceptionally low torque transmission loss of just **5.05×10^{-3} Nm**—far below typical values in conventional actuation systems. This minimal loss reflects precise load transfer, excellent component integration, and minimal energy dissipation, confirming the system's reliability under operational loads and validating the low-resistance design approach.

Internal power loss due to resistance was also found to be negligible. Further efficiency gains are possible through hull material optimization—using low-friction composites or surface-treated alloys could reduce internal drag while maintaining structural integrity.

Power Consumption Analysis

A direct comparison with a standard six-thruster configuration showed that the proposed system—utilizing **four high-efficiency servo motors and a single central thruster**—significantly reduces overall power consumption. This low-power actuation strategy enhances energy efficiency without compromising maneuverability or performance.

System	Power consumption	Runtime
Proposed system (1 servo + 4 thruster)	410 W	21.7 min
Conventional 6-thruster system	~2340 W	~3.8 min

Table 5: Power Consumption and Runtime Comparison

The proposed system achieves a **power consumption reduction of approximately 1930 W**, amounting to an **82.5% decrease** compared to conventional setups. This significant reduction not only conserves energy but also allows for the integration of smaller, lighter power sources—crucial for mobile and autonomous robotic platforms.

Runtime Advantage and Efficiency Gains

Due to the system's significantly lower power consumption, runtime increased from **3.8 minutes to 21.7 minutes**, extending operational time by **17.9 minutes**—a **5.7× improvement**. This substantial gain is especially valuable for applications requiring extended operation, such as underwater exploration, surveillance, or inspection missions.

This enhancement enables:

- **Longer mission durations** without the need for recharging or replacing power modules
- **Reduced heat generation**, leading to improved component lifespan
- **Increased design flexibility** for integrating additional sensors, AI modules, or payload systems

Conclusion

Simulation results confirmed the success and efficiency of the design. Strong numerical convergence was observed, with all residuals consistently decreasing from approximately **10^{-4} to 10^{-5} or lower**, and smooth, oscillation-free residual curves indicating excellent numerical stability. By the **100th iteration**, residuals had plateaued, confirming solution convergence.

From a design standpoint, **neodymium magnets** proved highly effective for torque transmission, ensuring minimal energy loss while maintaining system efficiency. The **structural integrity** of the hull remained intact throughout testing, and the overall **power consumption was significantly reduced**, demonstrating the design's energy efficiency.

The successful integration of magnetic coupling elements resulted in **negligible torque transmission losses**, validating both the **reliability and suitability** of the system for its intended underwater application.

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