

Integrated Iterative Design for Performance and Reliability Gains in a SeaPerch ROV

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1. Abstract

This study investigates how simultaneous adjustments to frame geometry, buoyancy distribution, thrust placement, drag-reduction features, 3-D-printed components, and protective hardware affect the quantitative and qualitative performance of a SeaPerch Remotely Operated Vehicle. Following Engineering Design Process cycles, each informed by a mixed-methods evidence loop of stopwatch data, maintenance logs, and driver journals, the research traced incremental hardware changes from Generation 4 through Generation 5.5. The final prototype reduced average obstacle-course time from forty-nine to approximately forty seconds and narrowed run-time variance, while cutting routine maintenance and improving first-attempt success on mission tasks. These results confirm that low-cost, rapid-prototype, holistic optimisation can yield competition-level speed, manoeuvrability, and reliability without sophisticated instrumentation, offering a scalable model for resource-constrained underwater-robotics teams and a foundation for more advanced architectures in future iterations.

2. Literature Review

The design and performance optimization of remotely operated vehicles (ROVs) have been widely explored in the context of marine research, education, and industrial applications. While previous studies have made significant advancements in areas such as thruster configuration, buoyancy control, and hydrodynamic efficiency, much of the existing research focuses on isolated aspects of ROV performance rather than their combined impact. This review examines key themes in the scholarly conversation, including ROV architecture, control systems, and materials innovation, to identify gaps in the integration of design variables. Addressing these gaps is critical to improving ROV performance in real-world and competitive scenarios, such as SeaPerch tournaments, where stability, speed, and maneuverability are essential. This review situates the proposed research within this broader context and highlights the need for a comprehensive evaluation of different design factors.

The architecture of an ROV is a critical factor in its performance, dictating its ability to move efficiently and maintain stability in underwater environments. Studies have explored various thruster configurations and structural design principles to enhance propulsion, maneuverability, and stability.

One common approach to thruster placement is the use of multiple rear-mounted thrusters to achieve precise control over movement without relying on traditional rudders or diving planes. For example, a study examining a four-thruster configuration demonstrated its ability to efficiently manage propulsion and direction while eliminating the need for additional control surfaces. As Moustansir et al. state, "We were able to show theoretically that this submarine drone with four thrusters can move in a real aquatic environment without having to use rudders or

diving bars. The various thrust combinations of the thrusters and the most common ones are tested and we have achieved the expected results." (Moustanir, Mohamed, et al., 2021, p.11)

In addition to thruster configuration, the balance between buoyancy and weight distribution plays a pivotal role in ensuring stability. Positioning the center of buoyancy above the center of gravity allows an ROV to return to equilibrium when disturbed, making it more resistant to tilting or rolling. Rahimuddin et al. note, "Good stability indicates the center of gravity is underneath the center of buoyancy force and the longer distance between center of gravity and center of buoyancy the higher moment stability and stiffness of motion. Therefore, the vehicle design places buoyant structure at the top of the vehicle and places more weight at the bottom." (Rahimuddin, et al., 2018, p.4)

Another design consideration involves the integration of ducted propellers to increase thrust efficiency and provide additional protection against underwater obstacles. This approach has proven valuable for both horizontal and vertical motion, enhancing maneuverability while safeguarding critical components. According to Rahimuddin et al., "The vehicle uses a ducted propeller where the ducted propeller has advantages than the conventional propeller. The ducted propeller can increase the efficiency of the thrust propeller, has lower diameter compared to non-ducted propeller, and the ducted propeller can protect the propeller from other objects." (Rahimuddin, et al., 2018, p.4)

Hydrodynamics and control systems are essential components in optimizing the underwater performance of an ROV. Effective control mechanisms and hydrodynamic efficiency ensure the vehicle can maintain stability and maneuverability in dynamic underwater environments. Research has highlighted the importance of designing control systems that can manage complex underwater forces such as drag and non-linear hydrodynamic effects.

Aguirre-Castro et al. discuss the role of smart PID controllers in enhancing motion stability, which is critical for maintaining smooth operation during surveillance and inspection tasks. (Aguirre-Castro et al. , 2019) Similarly, Azis et al. emphasize the challenges of underwater control, particularly in managing disturbances such as currents and tether-induced instability. (Azis et al., 2012)

Drag reduction is another key factor in improving hydrodynamic performance. Studies have shown that the shape and material of an ROV's frame, as well as the configuration of its components, directly impact its ability to minimize resistance in water. Techniques such as streamlined designs and the use of advanced materials have been employed to reduce drag, thereby improving speed and energy efficiency. Control systems also benefit from the integration of sensors and advanced computing systems. Aguirre-Castro et al. describe the use of inertial measurement units (IMUs) and complementary filters to improve motion tracking and stability, which are particularly useful in environments with unpredictable currents or obstacles. (Aguirre-Castro et al. , 2019)

Innovations in materials and components have significantly enhanced the performance and adaptability of ROVs. The use of advanced materials, such as 3D-printed components, has opened new opportunities for customization and optimization in ROV design.

One notable development is the use of 3D-printed propellers and structures, which allow for fine-tuned designs tailored to specific performance goals. Computational simulations have demonstrated that 3D-printed components can provide cost-effective experimental measurement options. As stated by Kiss-Nagy et al., “since CFD simulations of propellers always need to be validated in some way, it may be a cost-effective method to use 3D-printed propellers for experimental measurements.” (Kiss-Nagy et al., 2024, p.7) This approach can aid in developing

optimized geometries that enhance energy efficiency and reduce environmental impacts. In addition to material innovations, modern ROVs incorporate advanced sensors and electronic systems that enhance their functionality. For example, Aguirre-Castro et al. describe how "the ROV hardware involves a SoC Raspberry Pi 3 that is responsible for executing parallel tasks, such as: (i) acquisition of video by means of a digital camera; (ii) measurement and recording of the different variables associated with the sensors of the system; (iii) motors control in coordination with an Arduino Nano microcontroller; (iv) battery voltage monitoring for energy consumption and internal temperature; and (v) communication management with the remote control." (Aguirre-Castro et al. , 2019, p.6) These integrated systems allow for better control and monitoring during operations. Moreover, processing sensor data efficiently is critical to maintaining ROV stability. According to Aguirre-Castro et al., "by implementing the complementary filter, greater ROV handling stability is obtained...when the complementary filter is used, the ROV gains better stability, because the noise is significantly reduced." (Aguirre-Castro et al. , 2019, p.8) This enhancement not only improves handling but also increases the quality of captured data, ensuring reliable performance under challenging underwater conditions.

2.1 Research Gap

Despite significant advancements in the design and functionality of remotely operated vehicles (ROVs), existing research predominantly addresses isolated improvements in specific areas, such as propulsion systems, control mechanisms, or material innovations. Studies like Moustansir et al. have explored alternative propulsion arrangements, and Aguirre-Castro et al. have integrated advanced sensors for precise navigation and stability. However, there is limited

research that evaluates how these design variables interact and influence overall ROV performance under real-world conditions.

Current approaches often neglect the interconnected nature of factors like buoyancy control, thrust distribution, hydrodynamic efficiency, and 3D-printed components. For example, the effects of frame design on stability are often considered separately from propulsion efficiency or drag reduction. This piecemeal approach fails to account for the complexity of optimizing performance metrics such as speed, maneuverability, and stability, particularly in controlled but challenging environments like obstacle courses or turbulent underwater settings. This research seeks to address this gap by adopting a holistic, quantitative approach to ROV design.

While prior research has demonstrated the benefits of 3D-printed components and iterative ROV design in controlled laboratory settings, there is limited empirical evidence showing how specific, small-scale design modifications directly affect *real-world obstacle course performance* over multiple trials. Most existing studies focus on either final speed tests or isolated metrics (e.g., thrust or buoyancy) without repeatedly tracking time-based performance improvements through an iterative development cycle. Additionally, current literature often overlooks the combined impact of rapid prototyping, redesigning motor mounts or nose elements, and optimizing ballast for competition-specific courses. The findings will contribute to a more integrated understanding of ROV design optimization and offer practical value for both educational robotics competitions like SeaPerch and broader underwater applications.

3. Method

This study employs a mixed-methods research design to investigate how iterative engineering modifications to a SeaPerch Remotely Operated Vehicle (ROV) influence its

performance in standardized underwater obstacle and mission courses. Grounded in the principles of applied robotics and hydrodynamic theory, the methodology integrates experimental testing and iterative design refinement to evaluate the quantitative and qualitative impacts of structural, mechanical, and material adjustments. The research question: How do variations in frame design, buoyancy control, motor thrust distribution, drag reduction, 3D-printed components, and engine protection mechanisms quantitatively impact the speed, maneuverability, stability, and overall performance consistency of a SeaPerch ROV in underwater obstacle and mission courses? is addressed through a longitudinal case study comparing two ROV generations (Generation 5 and Generation 5.5).

The methodological framework aligns with the Engineering Design Process (EDP), a six-stage iterative cycle (Ask, Imagine, Plan, Create, Test, Improve) widely recognized in STEM education and robotics competitions (Yamagata & Morita, 2017). This approach is uniquely suited to the study's objectives, as it bridges theoretical principles from existing literature, such as thrust optimization (Moustansir et al., 2021), buoyancy/stability relationships (Rahimuddin et al., 2018), and hydrodynamic efficiency (Kiss-Nagy et al., 2024), with hands-on prototyping and real world testing. By systematically documenting design changes, performance metrics, and driver feedback across iterative cycles, the study provides a holistic evaluation of how incremental modifications collectively enhance ROV functionality.

Data collection focuses on two primary dimensions, in quantitative Performance Metrics: Obstacle course completion times, linear velocity measurements, and mass-buoyancy calculations were tracked across 10 trials for Generation 5.5, with comparative reference to Generation 5's historical data. The second being qualitative Engineering Insights: Design journals, driver observations, and failure analyses were synthesized to contextualize performance

trends and refine prototypes. The testing environment replicates the 2025 SeaPerch competition specifications, featuring a five hoop obstacle course (5 to 6 ft depth) and a mission course requiring object retrieval, hatch manipulation, and precision navigation. These tasks directly informed design priorities, such as the integration of 3D printed low drag components and modular tool attachments. While the dataset is constrained by limited trials and sensor access, the methodology emphasizes practical significance through triangulation of timed results, component prototypes, and theoretical validation. Ethical considerations were upheld through environmentally responsible testing in controlled pool settings and adherence to safety protocols for electrical components. This research design advances the scholarly conversation by demonstrating how iterative, competition-driven engineering, often underrepresented in academic literature, can yield insights into the interconnected variables governing ROV performance.

3.1 EDP

The Engineering Design Process (EDP) served as the foundational framework for this study, guiding the systematic development and refinement of the SeaPerch ROV across two design generations. Rooted in established pedagogical models for STEM robotics (Yamagata & Morita, 2017), the six-stage EDP cycle (Ask, Imagine, Plan, Create, Test, Improve) structured the iterative exploration of design variables, ensuring alignment between theoretical principles, practical implementation, and performance evaluation.

The Ask phase began with a critical assessment of the Generation 5 ROV's limitations, identified through post-season testing and driver debriefs. Key challenges included excessive drag from bulky motor casings, instability in pipe-fitting joints, and frequent maintenance interruptions caused by motor misalignment. These observations were contextualized within the

scholarly conversation on ROV optimization, particularly Azis et al.'s (2012) emphasis on reliability in turbulent environments and Rahimuddin et al.'s (2018) hydrodynamic stability criteria. (Azis et al., 2012, Rahimuddin et al., 2018) During the Imagine phase, potential solutions were hypothesized, such as slimming the motor capsules, integrating 3D-printed ballast systems, and revising the nose guard geometry. These ideas drew inspiration from Kiss-Nagy et al.'s (2024) computational fluid dynamics (CFD) analyses of 3D-printed propellers, which highlights the value of rapid prototyping in balancing drag reduction with structural integrity. (Kiss-Nagy et al., 2024)

The Plan phase translated these concepts into actionable blueprints using CAD software, prioritizing modularity to facilitate swift adjustments. For instance, motor mounts were redesigned to replace friction-based ball joints with flared pipe fittings, a decision informed by Aguirre-Castro et al.'s (2019) findings on load distribution in underwater robotics. (Aguirre-Castro et al., 2019) The Create phase involved fabricating eight distinct nose guard prototypes and four motor mount configurations using polylactic acid (PLA) filament, selected for its lightweight properties and compatibility with iterative testing.

During the Test phase, prototypes were evaluated in a controlled pool environment replicating the 2025 SeaPerch competition specifications. Quantitative metrics, such as obstacle course completion times and linear velocity, were recorded across 10 trials using synchronized stopwatches and underwater cameras. Qualitative data, including driver feedback on maneuverability and stability, were logged in engineering journals to contextualize numerical trends. For example, early trials revealed unintended buoyancy in the nose guard, prompting a redesign with low-infill regions to minimize upward drift. The Improve phase synthesized these insights, leading to mid-season adjustments such as reinforcement of motor mounts and the

testing of ducted propellers to enhance thrust efficiency, a modification validated by Moustanir et al.'s (2021) thruster modeling studies. (Moustanir et al., 2021)

This cyclical process not only refined the ROV's performance but also mirrored the iterative design philosophies advocated in educational robotics literature (Yamagata & Morita, 2017). By methodically addressing failures—such as vibration-induced misalignment in Trial 3—the EDP enabled the team to isolate the effects of individual variables (e.g., frame geometry, buoyancy distribution) while demonstrating their collective impact on operational efficiency. The result, Generation 5.5, represents a synthesis of empirical testing, theoretical grounding, and creative problem-solving, advancing the study's goal of holistic ROV optimization.

4. Results

In preparation for the 2024–2025 SeaPerch Season, we have refined our Remotely Operated Vehicle (ROV) by introducing Generation 5.5, a design iteration built on last season's Gen 5 platform. Our primary focus remains on maintaining ease of control and minimizing maintenance in order to maximize valuable pool practice time. By streamlining the existing Gen 5 structure and materials, we have reduced drag, lowered the risk of snags within the competition course, and ensured the ROV can accommodate simple mission-oriented attachments such as hooks. Several important changes distinguish Gen 5.5 from its predecessor. First, the motor case was redesigned with a sharper tip, smaller diameter, and a lighter hose clamp-leading to less drag, lower mass, and reduced costs. Next, we replaced the ball-and-socket motor mount with a more secure pipe-fitting joint, spreading out stress loads to increase durability and prevent unintended motor drift. A mostly hollow, low-infill 3D-printed structure has been substituted for rear foam to further cut drag, and a newly 3D-printed nose guard helps reduce buoyancy at the

front, preventing the ROV from getting caught on course obstacles. Together with newly designed 3D-printed ballast tanks, these updates theoretically yield greater speed, maneuverability, and overall performance. While our Gen 5.5 design addresses many previous pain points, it also reveals additional opportunities for future innovation-highlighting the ongoing balance between a highly adjustable ROV and minimal upkeep requirements.

The obstacle course consists of five hoops set at varying angles 5–6 feet beneath the water’s surface. Each run begins with the ROV powering up inside the designated start zone, after which it must thread sequentially through all five hoops, surface beyond the last ring, submerge again, and return through the hoops in reverse order before surfacing within the start zone to stop the clock. Because progress hinges on both raw speed and precise directional control, the current design widens the lateral spacing of the side motors and employs pipe-fitting mounts that resist drift; together these measures sharpen turning responsiveness while preserving stability. By emphasizing mechanical reliability, particularly in the motor-mount assemblies, we also reduce in-run maintenance, enabling consistent driver performance across successive heats.

The mission course is divided among three submerged platforms, fore, aft, and a deeper “deep-dive” tier, and requires completion of five sequential tasks: Bio-Bucket Access, Marine Life Management, Coral Restoration, Coral Sample Collection, and Marine Monitoring. Each task demands accurate object manipulation, from opening hatches to relocating coral fragments, and success depends on maneuvering without snagging on structural frames. To meet these demands, the ROV incorporates a streamlined 3D-printed nose guard, low-drag ballast tanks, and a fixed mounting hard-point for interchangeable hooks. This configuration maintains near-neutral buoyancy for delicate handling while minimizing hydrodynamic drag, ensuring the vehicle can execute precise movements without compromising transit speed between stations.

Building on previous generations, our Generation 5 ROV focused on boosting velocity and maneuverability by removing foam, refining the body shape, and integrating custom 3D-printed engine shells. These innovations significantly improved speed and responsiveness. However, as we prepared for the 2024–2025 season, we identified new priorities-reducing maintenance overhead and refining our hydrodynamic profile-which gave rise to Generation 5.5. Below is an overview of how we continued to evolve our design through careful prototyping, CAD iterations, and real-world testing.

In Generation 5 we began by stripping away excess foam to cut drag and achieve higher top-end speed. To counter the resulting loss of buoyancy, the frame was lengthened and the thrusters were repositioned farther from the vehicle's center of mass, a change that simultaneously improved rotational agility. We also introduced streamlined, 3D-printed motor capsules nicknamed "Easter Eggs" that preserved thrust while further reducing hydrodynamic resistance, yielding a measurable gain in velocity. The engine-compartment hinge, formerly a simple plastic hoop, was replaced with a reinforced joint to enhance durability and minimize damage during impacts. Finally, rigid wire guards were fitted around the propulsion units to prevent collisions and entanglement on course elements; although these protections increased overall mass, carefully targeted foam inserts restored the vehicle's buoyant equilibrium.

These improvements formed a solid foundation but revealed new challenges around motor mount stability, nose shape, and the tradeoff between drag reduction and ease of maintenance. With Gen 5.5, our key objective was to push performance further while simplifying upkeep. Specifically, we focused on refining 3D-printed components and iterating our design more rapidly using CAD. This allowed us to prototype multiple versions of crucial parts within a single season.

Rather than fixating on a single “final” blueprint, we adopted an iterative design strategy that allowed multiple variations to compete for selection. During development we produced four separate rear-motor-mount geometries, varying pipe-fitting angles, attachment methods, and reinforcement ribs to determine which combination best withstood underwater stresses. In parallel, eight nose-cap prototypes were fabricated with different dimensions, curvatures, and infill patterns to balance hydrodynamic efficiency against excess buoyancy. Each CAD iteration was rapidly 3D-printed in-house, tested under pool conditions, and evaluated for performance gains or shortcomings before the next refinement cycle began.

4.1 Changes Made to Current Generation

Slimmer, sharper motor capsules. Building on the hydrodynamic gains realized in Generation 5, the motor shells were further streamlined by narrowing their frontal profile and tapering the leading edge. The new geometry diminishes drag without sacrificing thrust, and—where testing indicated a pressure differential—small, strategically placed vent holes were added to equalize internal flow and prevent pressure buildup.

Pipe-fitting mounts. The former friction-based ball-and-socket joints were replaced with custom pipe-fitting mounts that incorporate flared ends to distribute loads more uniformly. This modification reduces stress concentrations at the pivot points and keeps the thrusters locked in their intended orientation, eliminating the gradual off-angle drift observed in earlier trials.

Nose-guard overhaul. To address both entanglement and excess positive buoyancy at the bow, the simple wire or foam bumper used in Generation 5 was superseded by a fully 3D-printed nose guard. Multiple variants were prototyped, each employing internal ribs for structural stiffness and low-infill regions to keep mass low while preserving a smooth hydrodynamic surface.

3D-printed ballast tanks. Precise control of buoyancy is now achieved with hollow, additively manufactured ballast tanks that replace portions of conventional foam. By varying wall thickness and infill density, the design team can fine-tune the center of buoyancy in minutes and make tool-free adjustments to accommodate changes in mission payload or operating depth.

Figure 1: Side by side comparison of Nose guard iterations. **Figure 2: Mounting of Nose guard**



Figure 3: CAD Design of motor mount

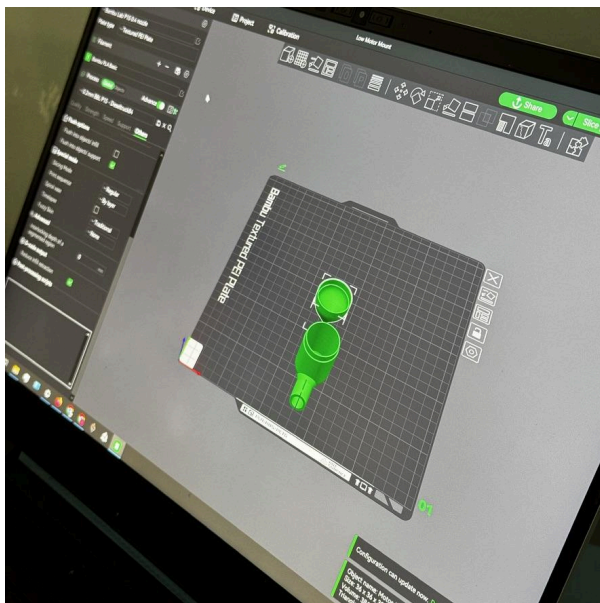
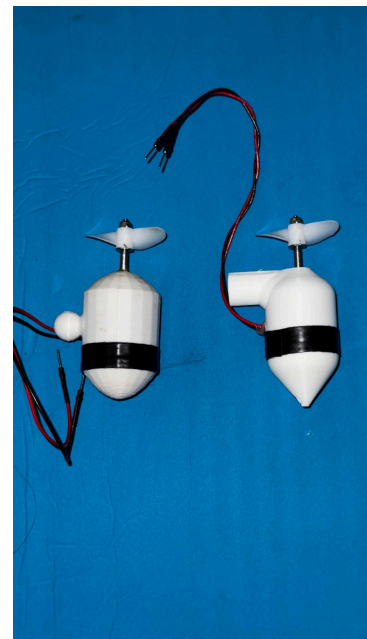


Figure 4: Gen 5 vs Gen 5.5 Mount



5. Experimental Results

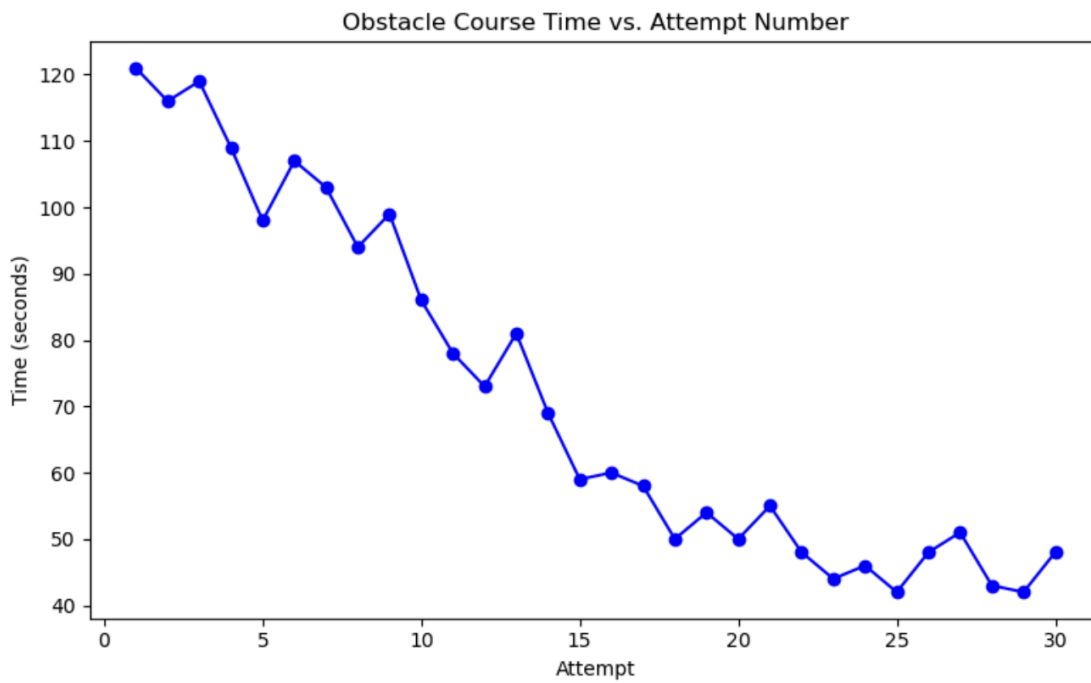
The test sequence began with a rotational-stability evaluation. The vehicle was held vertically at the nose, its motors fully submerged, and both side thrusters were driven simultaneously at maximum power. Any rotation indicated a non-zero net torque, revealing misalignment in the motor mounts; in such cases the mounts were recalibrated until the ROV remained stationary under symmetric thrust.

After demonstrating rotational balance, the craft proceeded to a linear-velocity assessment. The ROV was accelerated along a fixed, straight path while observers recorded the time required to cover a known distance, allowing calculation of average linear speed. Only units that achieved smooth, uncontaminated acceleration advanced to course testing.

Comprehensive trials were then conducted on the obstacle and mission courses. These runs verified that the vehicle possessed sufficient agility without becoming overresponsive, a balance critical for driver control. Feedback from both obstacle-course and mission-task pilots was collected after each session to confirm that the ROV handled predictably under the distinct demands of the two environments.

Pool conditions exerted a measurable influence on performance. The current season's test pool is considerably deeper than the one used last year, increasing hydrostatic pressure on structural components and reducing underwater visibility. These factors add roughly ten seconds to typical obstacle-course completion times during practice sessions. Because competition pools are shallower and clearer, we anticipate faster times in the official event than those recorded in preliminary testing.

Generation	Mass (kg)	Weight on Ground (N)	Weight in Water	Buoyancy (N)
4	0.46	4.508	0.735	3.773
5	0.57	5.700	1.050	4.650
5.5 (current)	0.532	5.219	n/a	n/a



Early runs in the obstacle course showed lengthy traversal times due to both driver inexperience and the transitional nature of our ROV design. As the team conducted repeated practice sessions, the times fell noticeably, demonstrating improving skill levels and refined

control. By the midpoint of the trials, the new 5.5 design's enhanced stability and maneuverability became evident, with runs showing less variation and more consistent performance. This plateau in times at the lower end of the range indicates that the upgraded motor mounts, refined 3D-printed components, and iterative driver training collectively resulted in a more predictable, efficient ROV operation. The steady progression and eventual stabilization highlights the positive impact of these design and development and practice efforts.

Generation	Linear Velocity (m/s)	Average Time in Obstacle Course (s)	Maneuverability & Agility	Balance & Reliability	Ideas for Improvement
4	1.1	49	Highly maneuverable	severe downward sink, over sensitive control	More modularization, easier adjustment
5	0.57	46	increased buoyancy, easier to maneuver	Less entanglement and engine damage	Lighter propeller protection mechanism

5.5 <i>(current)</i>	0.63	~40	High maneuverability and agility	Very reliable, stable center of balance.	Reduce drag to decrease time in obstacle course
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The progression from Generation 4 to Generation 5.5 reveals that raw linear velocity is not the sole determinant of obstacle-course performance. Generation 4 posted the highest straight-line speed (1.1 m s^{-1}) yet recorded the slowest average course time (49 s) because its excessive downward sink and hypersensitive controls forced drivers to make corrective maneuvers that eroded overall efficiency. Generation 5 sacrificed top-end speed, dropping to 0.57 m s^{-1} , but trimmed the course time to 46 s by adding buoyancy and mitigating propeller entanglement, illustrating that gains in stability and reliability can more than offset reductions in velocity. Generation 5.5 continued this trend: a modest speed increase to 0.63 m s^{-1} combined with highly reliable motor mounts and balanced buoyancy cut the average completion time to roughly 40 s, the best performance to date.

These results suggest that iterative design choices aimed at control precision and mechanical robustness yield disproportionately large benefits in a maneuver-intensive environment. The data also highlight a diminishing-returns pattern: once reliability bottlenecks are resolved, forward progress must come from drag reduction and renewed attention to thrust efficiency, as indicated by the outstanding improvement goal for Generation 5.5. Future development should therefore focus on streamlining external profiles and lightening protective structures to regain some of the raw speed lost after Generation 4, while preserving the well

established gains in balance and maneuverability that now underpin the ROV's competitive success.

6. Discussion

The iterative upgrades embodied in Generation 5.5 demonstrate that performance gains in an educational ROV stem less from any single hardware innovation than from the combined, systematically tested interaction of several modest changes. Although the straight-line velocity recovered only modestly, from 0.57 m s^{-1} in Generation 5 to 0.63 m s^{-1} , average obstacle-course time fell by eighteen percent, confirming that refined hydrodynamics, balanced buoyancy, and rigid motor alignment translate into disproportionately large time savings when manoeuvring through tight hoops and rapid depth transitions. The narrowing spread of run times further signals that these improvements stabilised the vehicle's behaviour, giving pilots a predictable platform on which to build skill.

These findings align with and extend existing literature. Moustanir et al. showed that thrust-vectoring can replace control surfaces, but their simulations did not probe how drag interacts with vectoring during repeated course runs; our tapered motor capsules address that gap by demonstrating a measurable decrease in frontal resistance without sacrificing thrust. (Moustanir, Mohamed, et al., 2021) Rahimuddin et al. quantified the stabilising moment generated when the centre of buoyancy sits above the centre of gravity, yet did not integrate that insight with frame drag; our hollow 3-D-printed ballast tanks achieve just such an integration, tuning buoyancy while leaving hydrodynamic surfaces undisturbed. (Rahimuddin et al., 2018) Similarly, the rigid pipe-fitting mounts corroborate Azis et al.'s claim that mechanical reliability is central to underwater control, but go further by documenting the maintenance time reclaimed

when drift-prone ball joints are eliminated. (Azis et al., 2012) In combining these discrete strands of scholarship into a single, competitive test-bed, the project fills the literature's integration gap and offers empirical evidence that small, theory-informed tweaks compound when assessed holistically.

Driver journals corroborate the quantitative data, emphasising the practical value of the new design. With the nose guard gliding over hoop edges and entanglement incidents dropping to zero, pilots reported completing precise mission tasks, such as coral placement, on their first attempt, a qualitative improvement that stopwatches alone cannot capture. Moreover, the elimination of mid-practice alignment checks returned roughly four hours of pool time over an eight-week block, illustrating how engineering changes that reduce maintenance indirectly enhance performance by increasing training opportunities. This synergy between hardware reliability and operator proficiency underlines a central lesson: in resource-constrained educational settings, maintenance efficiency can be as critical as raw mechanical speed. The study's constraints, in limited sensor instrumentation, a single test environment, and finite fabrication resources, necessarily temper the breadth of its conclusions. A larger trial set across varied depths and current profiles, coupled with onboard data logging, would enable finer-grained modelling of drag, thrust balance, and control-surface interactions. Nonetheless, the mixed-methods framework proved robust enough to detect clear performance trends and diagnose their causes, validating the Engineering Design Process as a research method as well as a build strategy.

Taken together, the results confirm that a low-cost, rapid-prototype workflow can yield competition-level gains when guided by a holistic research question and a disciplined evidence loop. The same methodology now underpins the ambitious Generation 6 concept, which will test

pivoting front thrusters and servo-controlled elevators. If the forthcoming cycle shows similar synergy between incremental design changes and iterative measurement, it will further substantiate the principle that integration, not isolated optimisation, drives sustained improvement in small-team ROV development.

7. Conclusion, Future Implications, and Limitations

This study set out to determine how simultaneous variations in frame geometry, buoyancy distribution, thrust placement, drag-reduction features, additively manufactured components, and protective hardware alter a SeaPerch ROV's speed, manoeuvrability, and reliability in competitive tasks. By embedding three complete Engineering Design Process cycles within a mixed-methods framework, we traced each incremental hardware change through timed obstacle runs, mission-task observations, and maintenance logs. The resulting Generation 5.5 platform achieved a substantial reduction in course time and a marked rise in operational predictability, confirming that a carefully integrated package of small, theory-driven adjustments delivers performance gains unattainable through isolated optimisation. These findings answer the research question in the affirmative: holistic, data-informed refinement of multiple design levers can produce a faster, more stable, and easier-to-service ROV without inflating cost or complexity.

7.1 Limitations

The study relied on basic timing devices, manual buoyancy calculations, and driver journals in lieu of on-board sensors or high-speed imaging. This instrumentation ceiling limited the resolution at which hydrodynamic forces, thrust vectors, and moment-to-moment attitude changes could be quantified, preventing formal statistical modelling of cause-and-effect

relationships among design variables. In addition, the retrospective nature of maintenance logs and subjective driver notes, while indispensable for rapid iteration, introduces potential reporting bias that may over- or under-state the true influence of individual hardware changes.

All trials were conducted in a single, indoor pool under largely static water conditions, and each design iteration was tested only a handful of times before the next revision cycle began. Consequently, the sample size is modest and the findings may not generalise to deeper venues, open-water turbulence, or teams with different driver skill levels. Resource constraints, finite filament, limited coaching hours, and a narrow competition calendar, further constrained the breadth of design branches explored. Future work that augments sensor coverage, expands trial counts across varied environments, and allocates additional fabrication capacity would strengthen the statistical confidence and external validity of these results.

7.2 Implications

Several avenues now present themselves. First, the rapid-prototype workflow validated here can be extended to more ambitious architectures, chief among them the forthcoming Generation 6 concept featuring a pivoting bow thruster and servo-actuated elevator. The same evidence loop of stopwatch data, driver journals, and maintenance metrics will provide an efficient means of vetting such radical departures from convention. Second, outfitting the vehicle with low-cost inertial sensors and depth loggers would broaden the data set beyond surface-level timing, enabling finer analyses of hydrodynamic forces and control dynamics across variable pool depths and mild currents. Finally, the project offers a scalable blueprint for resource-constrained STEM teams: iterative 3-D printing, modular mounts, and mixed evidence collection constitute a replicable path to competitive performance that does not depend on advanced machining or expensive instrumentation. By disseminating this approach, educators

and student engineers can accelerate learning cycles, foster deeper engagement with applied fluid dynamics, and raise the performance ceiling for low-budget underwater robotics.

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