

A Tether Management System for Hybrid Aerial–Aquatic Vehicles

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Hybrid aerial-aquatic vehicles have the potential to transform marine ecosystem monitoring, offshore infrastructure inspection, environmental surveying, and search-and-rescue operations by seamlessly transitioning between air and water. However, a persistent challenge limiting submerged operation is maintaining reliable communication: radio-frequency (RF) signals are rapidly attenuated underwater, and acoustic communication suffers from limited bandwidth and high latency. As a result, a tether (a physical cable linking the vehicle to the surface) remains essential for real-time command and data transmission. This work presents the design and implementation of a novel dynamic tether management system that enables continuous remote control of an aerial-aquatic vehicle through a surface buoy. Mounted directly on the vehicle, the system actively regulates tether length using a custom tension-sensing feedback mechanism to keep the buoy at the water surface while preventing excess slack that could entangle the vehicle. The tether system is integrated into a custom-built quadcopter-based platform featuring waterproofed electronics and tiltable thruster arms for underwater thrust vectoring. The complete system was validated in three operational underwater modes: descent, ascent, and horizontal translation. This demonstrated stable communication and tether control throughout. By addressing a critical limitation in underwater remote control, this work advances the design of hybrid platforms capable of precise operation across aerial and aquatic environments.

Introduction

Unmanned underwater vehicles such as remotely operated vehicles (ROVs) are typically controlled from a surface station via a tether, which transmits operator commands, telemetry, and in some cases power (Christ & Wernli, 2011). Real-time operator control is required for a range of demanding applications, including deep-sea exploration, pipeline inspections, and military operations (Bogue, 2015; Izadi Moud et al., 2018; Fun Sang Cepeda et al., 2023). The tether is usually designed to be neutrally buoyant to minimize the force exerted on the vehicle (INVOCEAN Group, 2025). More recently, broader reviews of unmanned underwater vehicles have contextualized ROVs within the growing ecosystem of hybrid and autonomous platforms, emphasizing communication, energy efficiency, and multi-domain operation as emerging design frontiers (Xu et al., 2024). Surveys of inspection-class underwater vehicles further highlight the key design considerations of tethered vehicles, including propulsion, buoyancy, and telemetry subsystems (Capocci et al., 2017).

Transmitting operator commands via a physical tether is essential because radio-frequency (RF) signals are rapidly attenuated in water. For example, at 915 MHz, the effective penetration depth in seawater is only 1–2 cm (Smolyaninov et al., 2018), making wireless communication infeasible for submerged vehicles. As a result, tethered communication remains the most reliable method for maintaining a control link during underwater operation.

However, the need for a tether creates significant challenges. The tether restricts mobility due to limited length, and the reaction forces it transmits can introduce random perturbations to the vehicle. Although longer or thinner tethers can partially alleviate these limitations, the presence of any tether prevents the vehicle

from being deployed as conveniently as a purely aerial platform. Hybrid aerial-aquatic vehicles have sought to address the limitations of conventional ROVs by reducing deployment complexity; several designs demonstrate fully submersible vehicles that can fly from a launch point to a distant water entry site before reconfiguring for underwater operation (Zeng et al., 2022; Pedroso et al., 2022; Lyu et al., 2022; Lu et al., 2018). One notable platform, Medusa, uses a quadrotor as a mobile surface base to deploy a tethered underwater pod for sampling missions (Debruyn et al., 2020). The quadrotor lands on the water surface and lowers the pod by releasing a tether from a spool. However, Medusa's underwater pod was constrained by a small payload capacity and relied on water-jet propulsion, resulting in limited speed and efficiency.

Because aerial-aquatic vehicles are also subject to the limitations of underwater RF propagation, most existing platforms operate autonomously once submerged, performing pre-programmed tasks or navigating through pre-configured waypoints (Bovio et al., 2006). While considerable research has focused on cooperative localization and mapping strategies for underwater vehicles, comparatively less attention has been paid to enabling direct, real-time operator-in-the-loop control (O'Neill et al., 2022; Papalia et al., 2022). Although autonomy plays a critical role in underwater robotics, there are important scenarios such as search and rescue and underwater infrastructure inspection where hybrid systems combining autonomous behaviors with real-time operator control are essential for adapting to dynamic uncertainties.

To address this gap, this paper presents a dynamic tether management system that remains docked on the vehicle and enables real-time remote control during submerged operation. The system employs an antenna attached to a floating buoy that remains at the

water surface, conveying communication signals to and from the vehicle via the tether. As the vehicle travels underwater, the buoy tracks the vehicle's motion, remaining positioned above it due to controlled tension in the tether. A concept for a typical deployment is depicted in Figure 1. By integrating the tether management system entirely onboard the vehicle, this design eliminates the need for surface-based infrastructure or ground crew, significantly reducing deployment complexity compared to conventional ROV operations.

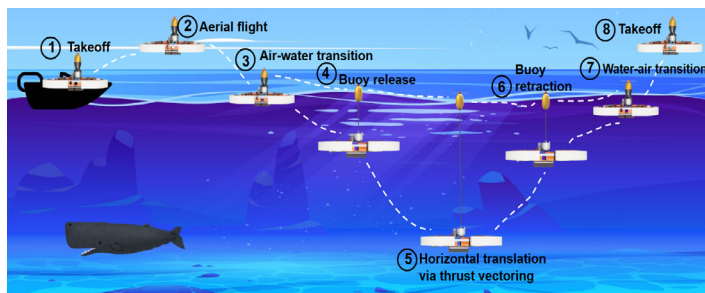


Figure 1. Full deployment and operation workflow: (1–3) aerial deployment and water entry, (4–6) submerged operation with dynamic tether and buoy management, and (7–8) resurfacing followed by aerial recovery.

Hybrid Aerial-Aquatic Vehicle Platform

The vehicle design (Figure 2) is based on a quadcopter frame with front and rear propellers mounted on tiltable arms capable of full 360-degree rotation. This tiltable-arm arrangement constitutes the vehicle's thrust vectoring capability: by rotating the front and rear motor arms independently, the vehicle can redirect its thrust vector in one dimension (pitch axis), enabling the same propellers to generate both lift in air and downforce underwater. This configuration is referred to herein as an "H-tilt" thruster layout because the two tilt axes and the vehicle body form an H-shaped kinematic structure when viewed from above. The same motors and propellers are used for both aerial and underwater propulsion. Underwater, the motors reach their maximum power output at only 40% throttle command due to the increased hydrodynamic load on the propellers and the current limitations of the electronic speed controllers. This results in a maximum underwater thrust of approximately 50% of the thrust generated in air, corresponding to approximately 9.8 N per propeller underwater, determined experimentally. As a result, motor commands for underwater control are scaled by a factor of 0.4 to ensure operation remains within the controller's safe and effective range.

The airframe is constructed from custom-machined carbon fiber plates and tubes, chosen for their high strength-to-weight ratio and rigidity, which are critical for minimizing vehicle mass while maintaining structural integrity during both aerial flight and underwater operation. To achieve positive buoyancy, closed-cell foam components are integrated into the frame, resulting in a net buoyant force of approximately 34.3 N against the vehicle's dry weight of 26.5 N. This means the vehicle requires 7.8 N of downward thrust to initiate submersion. Given that each of the four propellers generates up to 9.8 N of thrust underwater, the system achieves a combined downward thrust of approximately 39.1 N, yielding an effective underwater thrust-to-weight ratio of

approximately 5:1. This ratio provides sufficient control authority for submerged maneuvering, including the ability to overcome buoyancy and execute controlled descents, ascents, and horizontal translations.

All onboard electronics are protected through a conformal parylene coating applied via chemical vapor deposition, eliminating the need for bulky waterproof enclosures. The vehicle operates using a custom dual-mode flight control system deployed on a microcontroller (Teensy 4.1, PJRC, Sherwood, OR, USA), supporting both aerial flight stability and underwater maneuvering. In flight, the vehicle behaves like a conventional quadcopter. Underwater, the front and rear propeller arms tilt downward to generate downforce, and are biased forward or backward via differential tilt angles to achieve horizontal translation (referred to as differential vectoring in Figure 2). The system is capable of reaching speeds up to 1 m/s underwater, which is comparable to the cruise speeds of commercially available inspection-class ROVs in the same size category (Capocci et al., 2017).

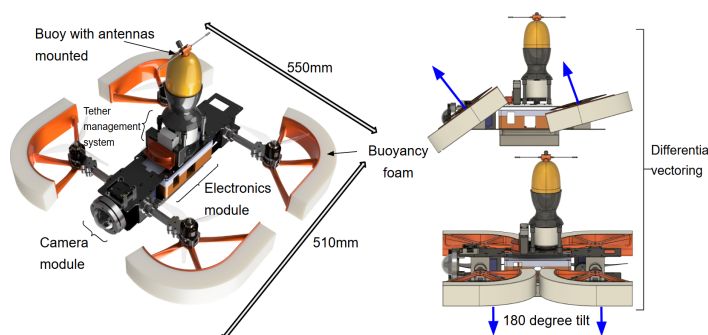


Figure 2. Full vehicle design highlighting key components and degrees of freedom. Differential vectoring refers to the independent tilting of the front and rear propeller arms to achieve combined downforce and horizontal thrust.

Tether Management System Design

The tether management system consists of three main components: a surface buoy with attached antenna, a tether connecting the buoy to the vehicle, and an onboard tether length management mechanism. As the vehicle operates at varying depths, the tether connecting it to the surface buoy must be carefully managed in length to ensure that the buoy remains at the surface for continuous radio communication. If too much tension is applied to the tether, the buoy risks being pulled underwater, compromising its ability to relay signals. On the other hand, releasing too much cable results in slack that raises the risk of entanglement with the environment or the vehicle's propellers, and causes sub-optimal buoy and antenna orientation at the surface. To address these challenges, the system dynamically adjusts the tether length in real time based on the tension state, which reflects the depth and horizontal motion of the vehicle. This ensures that the buoy remains afloat and stable on the surface while the vehicle retains freedom of motion underwater. The system also secures the buoy during aerial flight. By maintaining optimal tether tension, the system enhances the overall performance, safety, and operational flexibility of the vehicle during transitions between aerial and underwater modes.

Buoy Design

An ellipsoidal geometry was selected for the buoy because its continuously varying cross-sectional area produces a smoothly changing buoyancy force as the buoy is displaced vertically in the water. Unlike a cylindrical buoy, whose constant cross-section would produce an abrupt transition between fully floating and fully submerged states, the ellipsoidal shape creates a gradual, approximately linear relationship between submersion depth and upward buoyancy force over a useful operating range. This characteristic is important because it enables the tension-based control system to regulate buoy position with greater precision: small changes in tether tension correspond to proportional changes in buoy submersion, avoiding sudden jumps in force that would make the system difficult to control.

The buoy generates up to approximately 3 N of upward buoyancy force when fully submerged. This value was determined from the buoy’s displaced volume (approximately 306 cm³) and the density of water using Archimedes’ principle:

$$V_{\text{submerged}} \times g \approx 1000 \times 3.06 \times 10^{-4} \times 9.81 \approx 3.0 \text{ N}.$$

This buoyancy is sufficient to counteract the downward force exerted by the combined weight of a slightly negatively buoyant optical fiber tether when fully extended to a design depth of 100 meters, as illustrated in Figure 3.

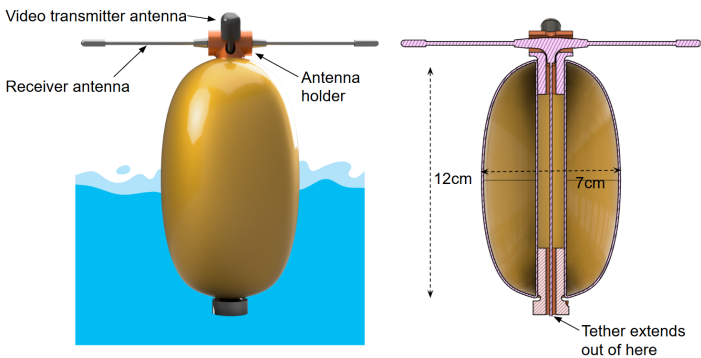


Figure 3. Buoy cross-section with attached antenna, showing key components and typical configuration when deployed.

Tension Sensing for Retraction

The tension in the tether provides sufficient information to determine how much of the buoy is submerged, since this tensional force balances with the upward buoyancy force generated by the buoy. A simple free-body diagram, as shown in Figure 4, demonstrates this force balance. With real-time feedback on the tether’s tension state, a closed-loop control system can continuously maintain a desired tension range corresponding to the expected buoyancy force when the buoy is partially submerged to the target level. This ensures that the tether remains slightly tensioned, thereby preventing slack that could result in entanglement with the vehicle’s propellers. Considering the case where the tether angle $\theta = 0$ (i.e., the vehicle is directly below the buoy), there exists an optimal buoyancy force, F_{optimal} , that the buoy experiences when it is partially submerged to the desired level.

The combined downward gravitational force of the buoy and fully extended tether is approximately 0.45 N. This value was calculated from the measured dry mass of the buoy (30 g) and the linear

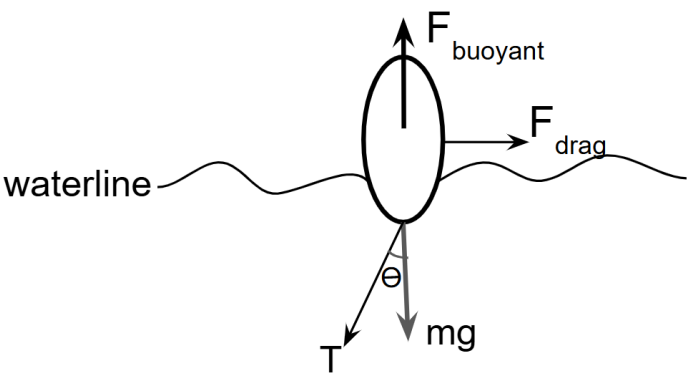


Figure 4. Free-body diagram of a partially submerged buoy showing the balance between buoyancy force (F_b), tether tension (T), gravitational force (mg), and the tether angle (θ).

density of the proposed optical fiber tether (approximately 1.2 g/m over 100 m), giving a total suspended mass of approximately 46 g and thus a gravitational force of $0.046 \text{ kg} \times 9.81 \text{ m/s}^2 \approx 0.45 \text{ N}$. This is much smaller than the maximum upward buoyancy force of 3.0 N when the buoy is fully submerged. Since this static gravitational offset remains constant across operating conditions and serves only to slightly shift the equilibrium position vertically, it can be neglected in a first-order analysis. With this simplification, the following relationships between tether tension and buoy position can be stated, as summarized in Table 1.

Condition	Buoy Position
$T \approx F_{\text{optimal}}$: partially submerged (ideal)	
$T \gg F_{\text{optimal}}$: fully submerged	
$T \ll F_{\text{optimal}}$: slack, unstable	

Table 1. Position of buoy with respect to tether tension.

F_{optimal} is determined by calculating the submerged volume of the buoy at the desired waterline position, as illustrated in Figure 5. The target waterline is set at approximately 60% submersion of the ellipsoid’s major axis. Using the volume formula for a partially submerged ellipsoid, $V_{\text{sub}} = (\pi ab/3)(3c - h) \times h^2/(c^2)$, where a , b , and c are the semi-axes and h is the submersion depth, the submerged volume at this target depth yields a buoyancy force of approximately 2.45 N (via $F_b = \rho_{\text{water}} \times V_{\text{sub}} \times g$). Accounting for the combined gravitational force of the buoy and tether (0.45 N), the net tether tension at the desired equilibrium is $F_{\text{optimal}} = 2.45 - 0.45 = 2.0 \text{ N}$. This is the tension setpoint used by the control system.

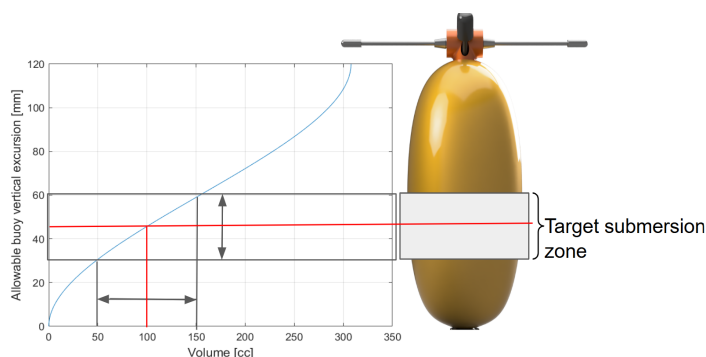


Figure 5. The desired submersion level of the buoy is used to calculate the submerged volume and thus the buoyancy force. The target waterline represented by the red horizontal line corresponds to approximately 60% submersion.

Tension Sensing Design

The system employs a single-point load cell (rated capacity: 5 N, resolution: ± 0.01 N) to measure the tension in the tether as it is wound or unwound about a spool. The tether is guided through a series of pulleys that redirect it while maintaining consistent tension. As the tether passes through the final pulley, the tension force is transmitted through a bracket that connects the pulley to the load cell. The final pulley is mounted on a bearing that allows it to rotate about the vertical axis, so that as the tether revolves around the spool during winding or unwinding, the force is always transmitted through the load cell's measurement axis, ensuring consistent readings regardless of the tether's angular position on the spool. Figure 6 shows the components of the spool and tension sensing system.

Control System Design

The control system architecture is shown in Figure 7. The system employs an adaptive proportional-derivative (PD) controller. The tether-buoy system exhibits behavior qualitatively similar to an overdamped system: when the buoy is fully submerged and the tether must be released to allow the buoy to breach the surface to the target zone, the buoy's upward thrust remains effectively constant and the tether tension changes gradually as cable is released or retracted. This results in a smooth, non-oscillatory approach to the tension setpoint without overshoot, which justifies treating the system as overdamped from a control perspective.

In this regime, a PD controller is sufficient. The proportional term drives the tension toward the setpoint, while the derivative term responds to rapid disturbances caused by vehicle motion or sudden changes in tension when the buoy breaches the surface and the submerged volume changes abruptly. An integral term was deliberately omitted: when the buoy is fully submerged, the tension tends to remain below the setpoint due to the constant buoyancy force, and a PD controller tolerates this small steady-state deviation. An integral term would accumulate this persistent error over time, causing the controller to respond more aggressively and potentially leading to overshoot or oscillations around the setpoint once the buoy nears the surface, undermining the otherwise smooth behavior of the system.

The adaptive nature of the controller involves modifying the proportional and derivative gains in real time based on the current length of deployed tether. These modifications compensate for the

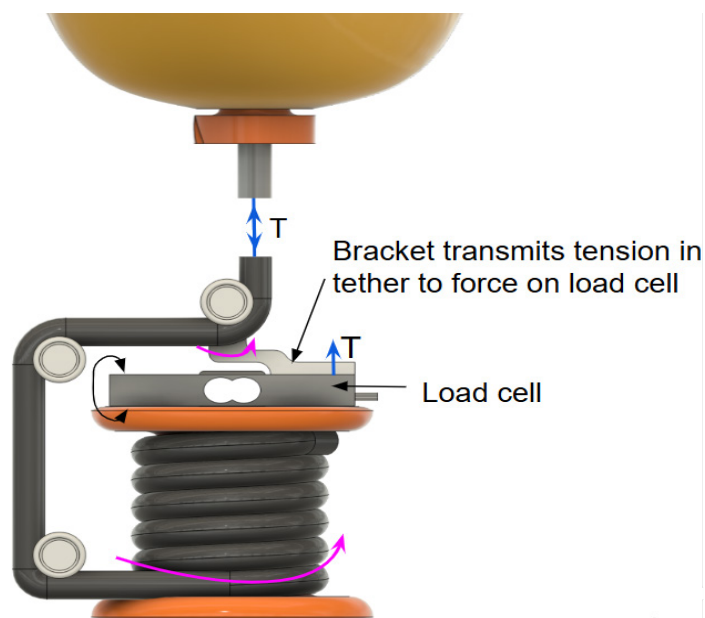


Figure 6. Spool design with load cell for measuring tension, showing the pulley routing, load cell bracket, and servo motor drive.

changes in the buoy's motion response characteristics as a function of tether length, as derived in the following section. The tension setpoint is $F_{\text{optimal}} = 2.0$ N, as determined in the tension sensing analysis above.

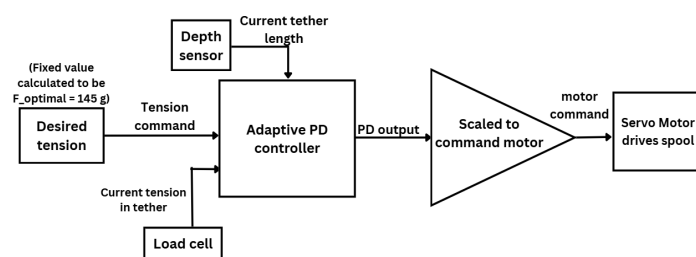


Figure 7. Control system block diagram showing the adaptive PD controller with tension feedback.

Motion Response

It is important to understand how tracking the desired tension (F_{optimal}) affects the buoy's behavior while the vehicle translates horizontally. The horizontal motion of the buoy can be modeled as a second-order linear system, as shown in Equation 1:

$$m_{\text{buoy}} \times \ddot{u} + c \times \dot{x} + (F_{\text{optimal}}/l) \times x = 0 \quad (1)$$

where m_{buoy} is the mass of the buoy, c is a velocity-dependent hydrodynamic drag coefficient, l is the current length of deployed tether, and x is the horizontal displacement of the buoy. This is a standard mass-spring-damper system with the effective spring constant $k = F_{\text{optimal}} / l$. The damping ratio ζ is given by Equation 2:

$$\zeta = \frac{c}{2\sqrt{F_{\text{optimal}} \times m_{\text{buoy}}/l}} \quad (2)$$

The system is expected to be overdamped ($\zeta > 1$) since the buoy should not overshoot or move ahead of the vehicle. As shown in Figure 8, the damping ratio increases with increasing tether length. In the current prototype, the maximum tether length tested was

10 m, constrained by the tank testing environment (described in the Experimental Methods section). At the design target of 100 m, the damping ratio is expected to be significantly higher, meaning the buoy will track the vehicle's horizontal motion more slowly at greater depths. This depth-dependent response is a fundamental characteristic of the system and must be accounted for by the adaptive controller, which adjusts its gains as a function of the deployed tether length to maintain adequate tracking performance across the full operating range.

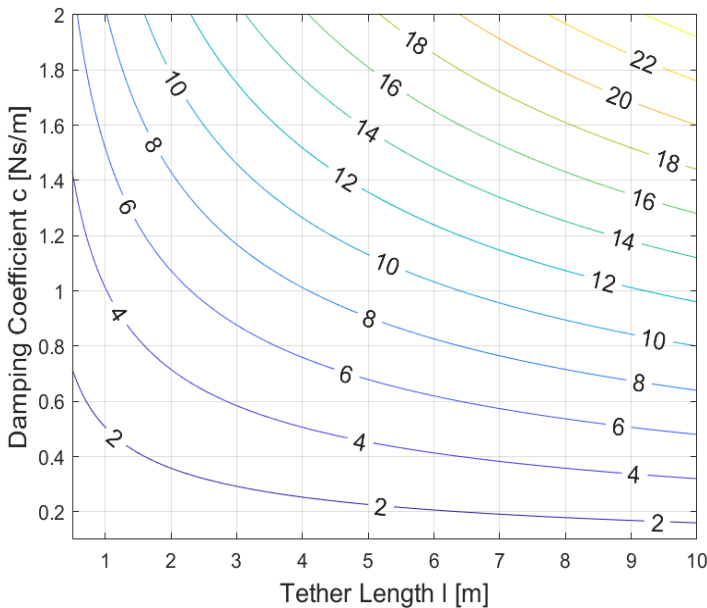


Figure 8. Characterization of damping ratio as a function of tether length and damping coefficient. The damping ratio increases with tether length, indicating reduced buoy responsiveness at greater depths.

Experimental Methods

For the purposes of this study, a lightweight string was used in place of a full optical fiber tether to validate the working principle of the tether management mechanism, focusing on system behavior and control without the added complexity of tether mass or stiffness. The proposed fiber optic tether design is described separately in the following section. The final assembled tether management system is shown in Figure 9.

The assembled system integrates the load cell for tension sensing, a servo motor to drive the spool for tether release and retraction, and the buoy to keep the antenna above the waterline. The system is mounted directly along the center of mass on the vehicle fuselage. The tether is connected to the flight controller on the vehicle, and the servo motor is powered from the vehicle's power system, as shown in Figure 2.

To validate the vehicle's transition from air to submerged operation, experiments were carried out in a test tank with dimensions 3 m × 3 m × 2 m. Given space constraints that precluded aerial flight within the test environment, the vehicle was manually placed on the water surface, where it then oriented its propellers downward to generate the necessary downforce for submersion. Since battery waterproofing is not addressed here, the system was powered via a tethered supply line.

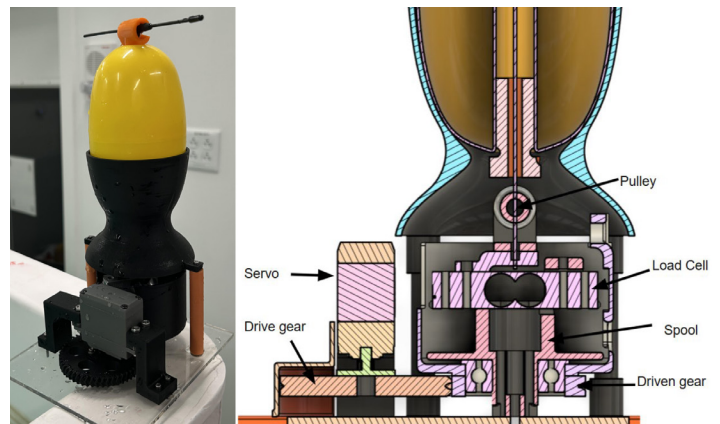


Figure 9. Test bench design of the tether management system highlighting key components including the spool, load cell, servo motor, and buoy.

The primary objective of the experiments was to evaluate the performance of the onboard tether management system during descent and horizontal translation. The vehicle's transition from aerial to underwater configuration is demonstrated in Figure 10.

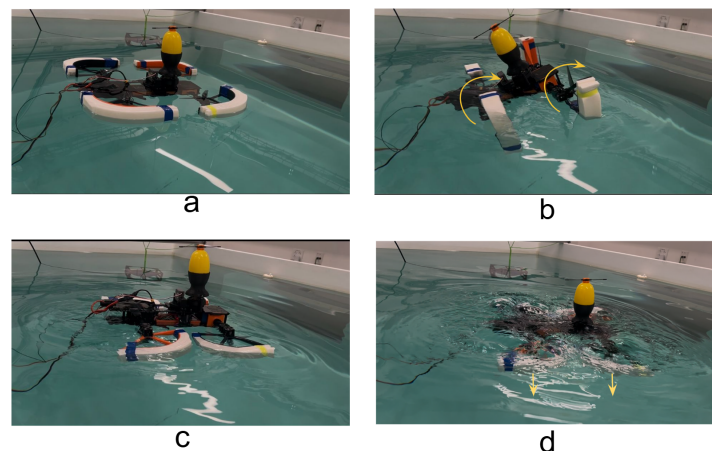


Figure 10. Sequence demonstrating the aerial to underwater transition. (a) Standard aerial flight configuration. (b) Propellers begin tilting downward. (c) Fully inverted position. (d) Vehicle initiates descent into the water.

Results and Discussion

The tether management system was evaluated during vehicle descent and horizontal translation in the test tank. During descent, as the vehicle submerged and increased its depth, the tether management system successfully released the buoy and regulated tether length to maintain the buoy at the water surface. Figure 11 shows a sequence from the descent test, demonstrating that the buoy remained partially submerged at the target waterline level throughout the vehicle's downward motion. The tension feedback loop responded to increasing depth by releasing tether at a rate that prevented both buoy submersion (which would indicate excessive tension) and slack accumulation (which would indicate insufficient tension).

During horizontal translation, the buoy tracked the vehicle's lateral motion as predicted by the motion response model. Figure 12 illustrates the forward and backward tracking behavior. The buoy followed the vehicle's horizontal position with a lag

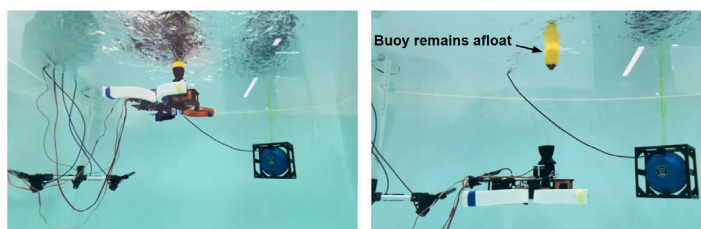


Figure 11. Demonstration of the buoy remaining partially submerged at the target waterline as the vehicle descends.

consistent with the overdamped response characteristics described by Equations 1 and 2. No oscillation or overshoot of the buoy was observed, confirming the appropriateness of the PD controller and the overdamped system model.

Throughout both descent and horizontal motion tests, the radio communication link between the operator and the vehicle was maintained without interruption, confirming that the buoy's surface position was preserved within the acceptable range. These results validate the core operating principle of the tension-based tether management approach: by controlling tether tension rather than directly measuring depth or buoy position, the system achieves robust performance without the need for additional environmental sensors that could be subject to drift or calibration errors in underwater conditions.

Several limitations of the current prototype should be noted. First, the experiments were conducted in a controlled tank environment with calm water; performance in open-water conditions with waves, currents, and turbulence remains to be evaluated. Second, the lightweight string used as a tether substitute does not capture the mass, stiffness, or drag characteristics of a full optical fiber tether, which may affect system dynamics at greater depths. Third, the maximum tested tether length was limited to approximately 2 m by the tank depth, well below the 10 m range modeled in the motion response analysis and the 100 m design target. Finally, battery waterproofing was not implemented, requiring the use of an external power supply tether that may have introduced additional drag and disturbance forces during testing.

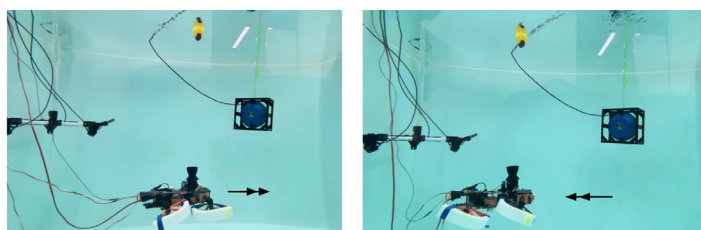


Figure 12. The forward and backward motion of the vehicle is tracked by the buoy, demonstrating the horizontal tracking capability of the tether management system.

Conclusion and Future Directions

This work presented the design, analysis, and experimental validation of a dynamic tether management system for hybrid aerial-aquatic vehicles. The system addresses a fundamental limitation in underwater remote control by providing continuous, reliable communication between an operator and a submerged vehicle through a surface buoy managed entirely by onboard

mechanisms. The key contributions of this work include: the development of a tension-based feedback approach that regulates tether length without requiring depth sensors or environmental measurements; the design of an ellipsoidal buoy that provides a smoothly varying buoyancy force suitable for closed-loop tension control; an analytical model of the buoy's horizontal motion response as a function of tether length, informing the design of an adaptive PD controller; and experimental validation of the complete system during descent and horizontal translation in a controlled environment.

The proposed system has direct applications in several domains where real-time operator control of submerged vehicles is essential. In offshore infrastructure inspection, the vehicle could enable operators to visually inspect underwater structures such as bridge pilings, pipelines, and offshore platform foundations while maintaining a real-time video link. For marine ecosystem monitoring, the system could allow researchers to conduct targeted biological sampling or observation of aquatic organisms with direct operator guidance. In search-and-rescue operations, the ability to deploy from air and transition to controlled underwater search patterns without pre-programming could significantly reduce response times and improve situational awareness in dynamic environments.

To support full-scale deployment, the current string-based tether used for prototype validation would be replaced by a single-mode optical fiber link. In this architecture, the buoy would house a radio antenna, a radio receiver module, and a single-board computer (Raspberry Pi 4 Model B) serving as the central processor. Operator commands received via the radio link would be processed onboard the buoy and transmitted down to the vehicle through an Ethernet-to-fiber-optic media converter. On the vehicle side, a corresponding media converter would translate the optical signal back to Ethernet, routing data to the flight controller and video transmitter. This fiber optic approach offers several advantages over the string substitute: it provides the bandwidth necessary for real-time HD video streaming alongside control commands and sensor telemetry, introduces negligible signal latency over the target 100 m operating depth, and its slight negative buoyancy is already accounted for in the buoy and tension control design presented in this work.

Several additional steps remain before the system is ready for field deployment. The fiber optic tether must be integrated and its communication performance validated at extended depths up to 100 m. The tether management system must then be tested in open-water environments where waves, currents, and wind introduce disturbances absent from the tank experiments. Onboard battery waterproofing must be implemented to eliminate the external power supply tether used in the current prototype. The adaptive controller gains must be tuned and validated across the full range of tether lengths from 0 to 100 m, as the motion response model predicts significantly different buoy dynamics at these extremes. Finally, autonomous path-planning algorithms that account for the tether's geometric constraints could be developed to complement the operator-in-the-loop control mode, enabling hybrid autonomous-manual operation for complex missions.

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