

EFFECT OF BALLAST POSITION ON VERTICAL STABILITY AND EFFICIENCY OF A SMALL-SCALE BUOYANCY-DRIVEN UNDERWATER GLIDER

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Abstract

Underwater gliders rely on buoyancy-driven motion for long-duration, energy-efficient ocean monitoring, but their stability and performance depend strongly on mass distribution. This study evaluates how ballast position affects vertical dynamics and buoyancy-driven energy-conversion efficiency in a 50 cm cylindrical, syringe-based buoyancy glider tested in a laboratory tank under sinking and floating conditions. Three ballast position ratios ($\lambda_b = 0.2, 0.4$, and 0.5) were selected (forward, intermediate, near-midpoint) to capture the transition toward stable vertical motion under reproducible, prototype-constrained conditions. Vertical velocity, buoyancy-driven energy-conversion efficiency (defined as useful buoyancy power divided by electrical input power), and orientation angles (pitch and roll) were measured using video tracking and an MPU6050 sensor. In this work, maximum efficiency refers to the ballast configuration that maximizes this energy-conversion ratio while exhibiting stable pitch and roll, which indicate vertical-motion stability. Results show that forward ballast ($\lambda_b = 0.2$) produced steep pitch angles exceeding 100° , reduced displacement to 15 cm, and yielded low efficiency (~13–15%). Shifting the ballast aft improved performance, with the midpoint configuration ($\lambda_b = 0.5$) achieving near-vertical alignment, symmetric ascent and descent, higher velocity (~0.045 m/s), and the highest efficiency (~23%). The relative roll response remained more stable across all cases, confirming that pitch dynamics dominate performance. The study concludes that optimal ballast placement near the midpoint maximizes stability and buoyancy-driven energy-conversion efficiency, offering a simple yet effective design principle for improving small-scale buoyancy-driven gliders.

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Keywords: underwater glider, buoyancy engine, ballast position ratio, stability, efficiency

Introduction

Water covers more than two-thirds of Earth's surface, and the oceans play a central role in regulating climate biogeochemical cycles, and human livelihoods [1]–[3]. Yet, despite their importance, much of the underwater environment remains poorly charted, particularly in deeper and more challenging regions. Because direct human access to such environments is constrained by depth, pressure, and endurance, technological solutions have become the primary means of observation and monitoring [4],[5]. A variety of autonomous or remotely operated systems have been developed for this purpose, each suited to specific operational niches [6]–[8].

Remotely operated vehicles (ROVs), which remain tethered to surface vessels, are often used for inspection, repair, and detailed sampling, benefiting from continuous power and real-time operator control [9]–[11]. Autonomous underwater vehicles (AUVs), on the other hand, carry out preprogrammed missions without external links, enabling them to collect data across larger spatial and temporal scales [12]–[14]. Within the broader class of AUVs, underwater gliders offer a distinctive approach. Instead of propellers or thrusters, gliders adjust their buoyancy to ascend and descend through the water column, translating these vertical motions into forward progress using wings and control surfaces [15]–[16]. This buoyancy-driven approach significantly reduces energy requirements, extending mission endurance to weeks or months, making gliders attractive for long-term environmental monitoring, ecosystem mapping, and surveillance [17]–[19].

The operational advantages of gliders stem from their buoyancy engines, which alter the vehicle's density relative to the surrounding water [20]–[21]. By pumping fluid in or out of a variable-volume reservoir, the glider changes its displacement, allowing it to sink or rise. Because this mechanism eliminates continuous thrust, it reduces both power consumption and mechanical complexity, while minimizing acoustic noise, a feature particularly valuable when monitoring sensitive marine habitats [16],[22],[23]. The effectiveness of the buoyancy engine directly influences the speed, stability, and energy efficiency of the glider [24]–[27].

While large-scale gliders are already in widespread scientific use, smaller prototypes are increasingly relevant for shallow waters, coastal environments, and experimental research [20],[28],[29]. Scaled-down designs allow for cost-effective testing of design concepts and serve as platforms for validating control strategies. However, miniaturization also introduces specific challenges. Smaller gliders are more sensitive to hydrodynamic disturbances and mass distribution effects, which can compromise both stability and efficiency. The literature has primarily focused on optimizing buoyancy systems for endurance, yet comparatively fewer studies have investigated how mass distribution interacts with buoyancy-driven performance, particularly in laboratory-scale gliders [30]–[33].

The present research addresses this gap by experimentally investigating a small-scale underwater glider equipped with a syringe-based buoyancy engine. Following a low-cost prototype development and

experimental validation approach commonly adopted in embedded mechatronic systems [34], the prototype was constructed with a 50 cm cylindrical body and designed to vertically displace itself by alternately inducing positive and negative buoyancy. The investigation focuses on how the placement of additional ballast influences performance, with the ballast position ratio defined as $\lambda_b = x/L$, where x is the distance from the nose of the glider (reference point) to the ballast center, and L is the total body length. Three values of λ_b (0.2, 0.4, and 0.5) were tested to examine their effects on vertical motion and stability.

Performance in this study was assessed through measurements of average vertical velocity, buoyancy-driven energy-conversion efficiency, and the orientation angles of pitch and roll. Average velocity was calculated from the time required for the glider to complete a fixed vertical displacement, while buoyancy-driven energy-conversion efficiency was expressed as the ratio of useful buoyant power output to the electrical power supplied to the system. Pitch angle represented the longitudinal orientation of the glider, and roll angle reflected its lateral stability. These parameters were examined during both negative buoyancy (sinking) and positive buoyancy (floating) phases to evaluate the degree of symmetry between descent and ascent. Through this combined approach, the study explores how variations in ballast placement affect the capacity of the glider to maintain stable alignment and to convert buoyancy energy into effective vertical motion.

The results of this work provide a reproducible experimental framework for testing simplified glider prototypes while also emphasizing the decisive influence of ballast positioning on velocity, energy-conversion efficiency, and orientation stability. The outcomes suggest that careful adjustment of mass distribution can improve endurance, stability, and control in small-scale underwater gliders. More broadly, these findings contribute to the ongoing refinement of buoyancy-driven technologies, supporting their development as reliable and energy-efficient platforms for marine exploration and environmental monitoring.

Research Methods

The experimental setup was developed to evaluate the buoyancy-driven actuation of a simplified underwater glider prototype. The methodology emphasizes clarity, reproducibility, and a direct linkage between system design and functional testing. The prototype design, illustrated in Fig. 1, is based on a cylindrical configuration using a 5-inch PVC pipe as the primary housing. The ends of the pipe are sealed with a pipe cap and a pipe cleanout, creating a watertight chamber to accommodate the buoyancy engine and associated electronics. The construction of the underwater glider prototype is illustrated in Fig. 1(a), which presents the fabricated system with its main components identified. The design consists of a cylindrical body made from a 5-inch PVC pipe, sealed at one end with a pipe cap and at the other with a pipe cleanout, forming a watertight housing. Inside the pipe, an acrylic case protects the buoyancy control mechanism and electronics from direct water exposure.

The buoyancy system is implemented using a syringe-based variable-volume reservoir (150 mL) actuated by an MG996R servo motor. The motor drives a lead screw through a flexible coupling, and the resulting rotation is converted into linear motion by a lead screw nut and plunger linkage to translate the syringe plunger. This arrangement enables controlled water intake to generate positive and negative buoyancy. The actuation and logging hardware are integrated within the acrylic enclosure and include an ESP8266 microcontroller with a servo driver, an SD-card module for data storage, and an MPU6050 IMU for measuring pitch and roll. The system is powered by two 3.7 V Li-ion batteries connected in series (7.4 V nominal). The assembled buoyancy-engine module and its main mechanical and electronic components are labeled in Fig. 1(b).

Experimental validation was carried out in a controlled tank environment to characterize the buoyancy response and stability of the underwater glider platform. The experimental arrangement is summarized in Fig. 2(a). A glass tank (80 cm × 60 cm × 60 cm) was filled to approximately 80% of its capacity to maintain consistent testing conditions, and a checkerboard background with 50 mm grid squares was installed to provide a visual reference for displacement measurement. A photograph of the submerged prototype during testing is shown in Fig. 2(b). The syringe-based buoyancy engine was actuated to generate both positive and negative buoyancy, inducing vertical motions. The maneuvers were recorded with a smartphone camera (30 fps) mounted on a tripod and aligned perpendicular to the tank. Frame time stamps were used to order the image sequence and to compute the elapsed time for each sinking (t_s) and floating (t_f) cycle. This enabled extraction of vertical displacement histories with temporal resolution sufficient to compute average velocities. Vertical velocity (v_{avg}) was obtained by dividing the measured displacement (20 cm or 15 cm, depending on configuration) by the elapsed time between the first and last frames of each sequence. This provided a direct measure of average ascent and descent rates under each ballast condition.

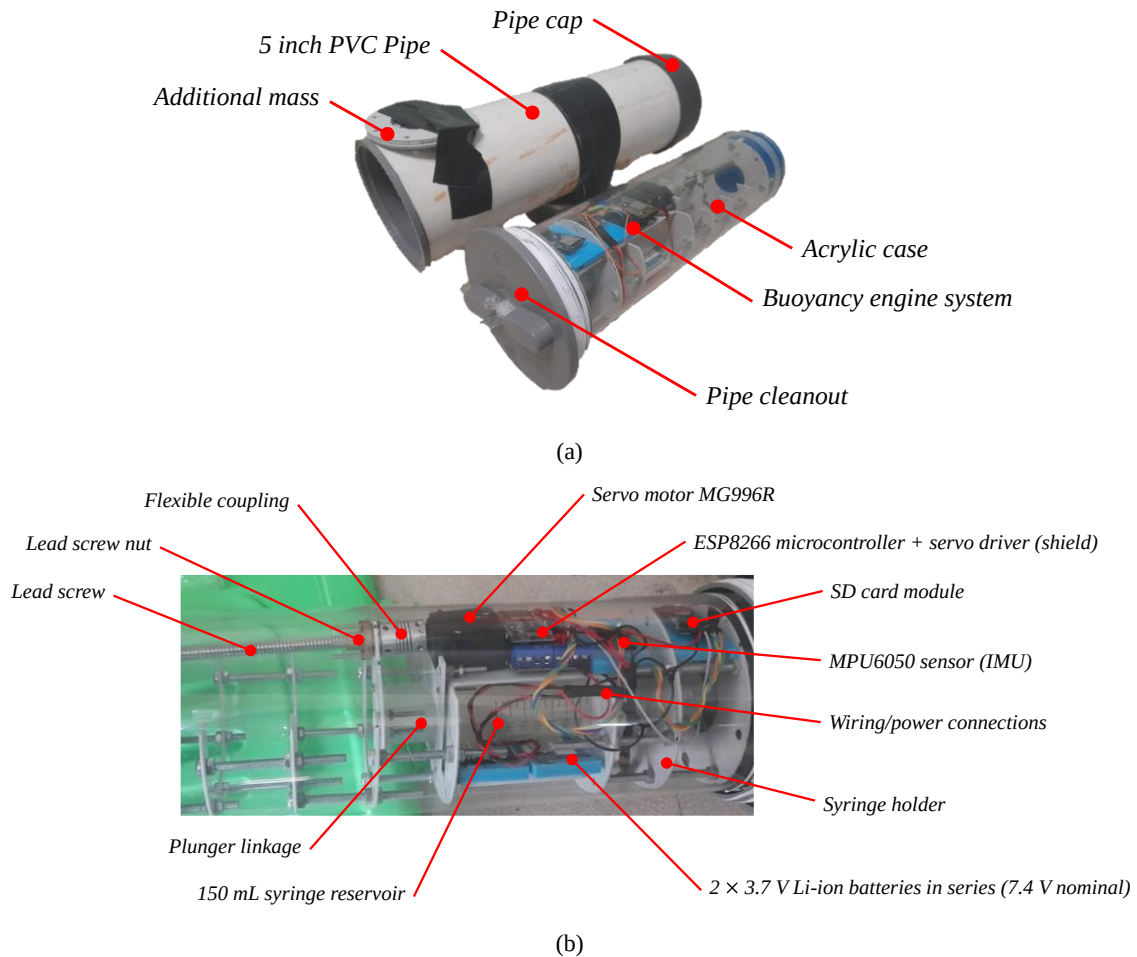


Figure. 1. Underwater glider prototype: (a) fabricated body components, (b) assembled syringe-based buoyancy engine with servo-driven lead screw actuation, 150 mL reservoir, and onboard electronics (ESP8266, MPU6050 IMU, SD-card module) powered by a 7.4 V nominal Li-ion supply.

To investigate the influence of mass distribution on the dynamic response of the proposed underwater glider, controlled variations in the placement of additional ballast were introduced along the length of the cylindrical platform. The ballast position ratio, denoted as λ_b , is defined in Eq. (1), where x is the distance of the ballast from the front end (reference point near the syringe assembly), and L is the total body length of the glider (50 cm in this study).

$$\lambda_b = \frac{x}{L} \quad (1)$$

Fig. 3 illustrates the three experimental configurations tested, where the ballast mass of 0.295 kg was systematically positioned at different longitudinal locations. In the first configuration, shown in Fig. 3(a), the center of the ballast was placed at $x = 10$ cm, corresponding to $\lambda_b = 0.2$. In the second configuration, depicted in Fig. 3(b), the center of the ballast was positioned at $x = 20$ cm, corresponding to $\lambda_b = 0.4$. Finally, in the third configuration, illustrated in Fig. 3(c), the center of the ballast was placed at $x = 25$ cm, giving $\lambda_b = 0.5$. Configurations with $\lambda_b > 0.5$ (aft of the midpoint) were not tested.

Although a perfectly fore–aft symmetric body could suggest mirrored behavior, the present prototype is referenced from the front end near the syringe assembly and includes a non-symmetric internal layout; therefore, aft-of-midpoint placements may not replicate forward cases. In addition, mounting positions aft of the midpoint are limited, and this study focuses on quantifying stability improvement up to the midpoint, where ascent–descent symmetry is expected to peak for this cylindrical configuration under repeatable test conditions. These incremental shifts in ballast location were designed to evaluate how mass distribution, expressed through λ_b , influences the center of gravity and consequently the hydrodynamic stability and vertical motion characteristics of the glider.

The stability of the underwater glider was evaluated using an MPU6050 six-axis inertial measurement unit (IMU), which integrates a tri-axial accelerometer and a tri-axial gyroscope to estimate the vehicle's pitch and roll angles for assessing vertical-motion stability [35]–[37]. Before each experimental run, the sensor was calibrated by keeping the glider stationary in a level (horizontal) reference orientation for a short baseline period to estimate gyroscope bias and accelerometer offsets, subtracting these offsets from subsequent measurements (bias compensation). Under the angle convention used in this study, a level (horizontal) body orientation corresponds to approximately 90° ; therefore, calibration was verified by checking that the measured pitch and roll remained close to 90° (within a small tolerance) under the same static reference condition. This approach is consistent with prior implementations that use MPU6050-based pitch measurements for underwater-glider attitude feedback and motion analysis [38],[39].

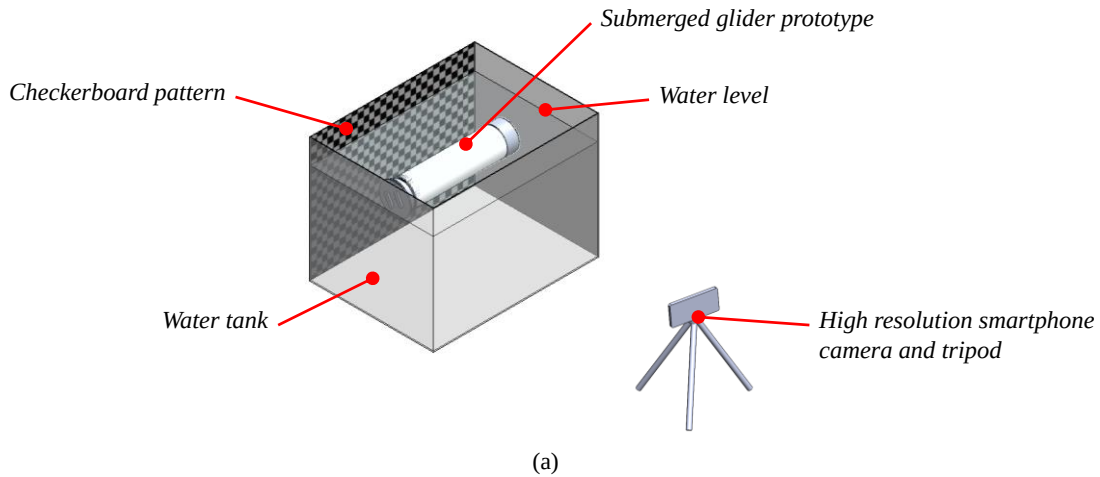


Figure 2. Experimental tank test for video-based displacement tracking: (a) schematic of the setup (checkerboard background, water level, and camera position), (b) submerged prototype in the test tank with the checkerboard reference

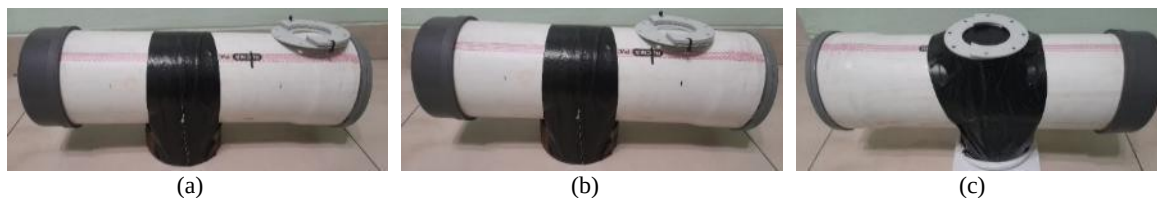


Figure 3. Experimental configurations showing additional ballast placement corresponding to ballast position ratios (a) $\lambda_b = 0.2$, (b) $\lambda_b = 0.4$, and (c) $\lambda_b = 0.5$

Data were recorded at an effective sampling frequency of approximately 83 Hz, as determined from the logged time intervals, over the duration of each sinking and floating cycle. The average pitch and roll values were computed across the sequence. The variability between repeated trials was expressed as the standard deviation, reported as $\pm$ values in the results. The pitch angle indicates stability along the lateral axis, while the roll angle reflects longitudinal stability. These measurements provided critical information on the ability of the glider to maintain orientation during submerged operations, as stable pitch and roll angles are essential for efficient navigation and controllability underwater. Before conducting performance trials, a leak test was

performed to confirm the integrity of the sealed housing. The model was submerged for 30 minutes, and no leakage was detected, ensuring that the buoyancy engine and electronic components operated reliably under experimental conditions.

Performance tests were repeated three times for each ballast configuration. The reported values of velocity, buoyancy-driven energy-conversion efficiency, pitch, and roll represent the mean of these replicates, with uncertainties expressed as the standard deviation across trials. Consistency across trials validated the methodology and reinforced the reliability of subsequent data analysis. To quantify energy performance, buoyancy-driven energy-conversion efficiency was defined as the ratio of buoyancy power to electrical input power, as expressed in Eq. (2):

$$\eta = \frac{\text{Buoyancy Power Estimation}}{\text{Electrical Input Power}} \times 100\% = \frac{F_A \cdot v_{avg}}{V \cdot I} \times 100\% \quad (2)$$

Here, the electrical input power was obtained as the product of supply voltage (V) and measured current (I), while buoyancy power was calculated as the product of buoyant force (F_A) and average vertical velocity (v_{avg}). The buoyant force was estimated using Archimedes' principle, where $F_A = \rho g V_d$, with ρ as the density of water, g as gravitational acceleration, and V_d as the displaced water volume. This framework enabled direct evaluation of the trade-offs between stability, speed, and energy-conversion efficiency under varying mass distributions and buoyancy conditions, thereby providing a systematic approach to assess the operational effectiveness of the proposed underwater glider.

Results and Discussion

The first case, shown in Fig. 4, presents the sinking (t_{s50}) and floating (t_{f50}) sequences when the ballast is placed at the midpoint of the body of the glider ($\lambda_b = 0.5$). At $t_{s50} = 0$ s the glider is nearly upright, and by $t_{s50} = 1.035$ s and $t_{s50} = 2.070$ s it maintains a vertical orientation with only minor nose-down tilt. At later times ($t_{s50} = 3.105$ s and $t_{s50} = 4.140$ s), the descent remains straight and stable, showing minimal oscillation. The floating sequence mirrors this trajectory: from $t_{f50} = 0$ s through $t_{f50} = 4.252$ s, the glider ascends with only small nose-up corrections, completing the 20 cm vertical displacement. This symmetry between sinking and floating demonstrates that the platform is dynamically balanced, converting buoyancy energy efficiently into vertical motion.

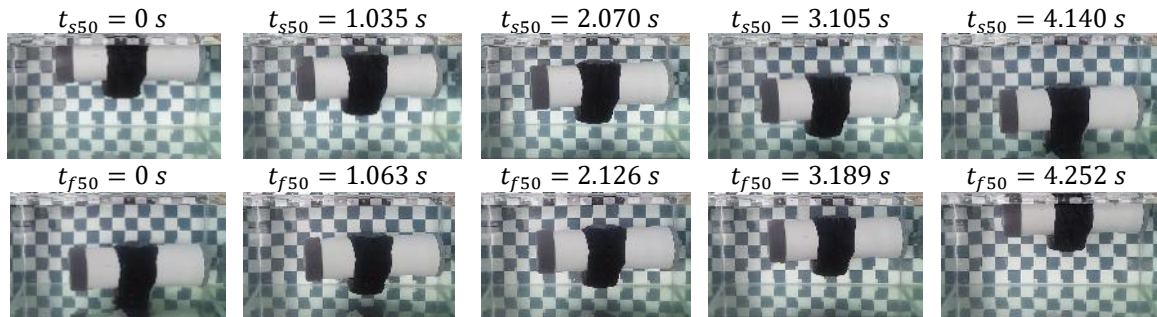


Figure 4. Sequential sinking (top row) and floating (bottom row) motions of the underwater glider with ballast position ratio $\lambda_b = 0.5$

The second case, shown in Fig. 5, corresponds to a ballast ratio of 0.4, slightly forward of the midpoint. At $t_{s40} = 0$ s, the glider starts upright but with a mild nose-down pitch that becomes more evident at $t_{s40} = 1.193$ s and $t_{s40} = 2.386$ s. By $t_{s40} = 3.579$ s and $t_{s40} = 4.772$ s, the orientation stabilizes, though the trajectory is angled rather than strictly vertical. The floating sequence shows the reverse pattern: from an upright start at $t_{f40} = 0$ s, the nose tilts upward by $t_{f40} = 1.408$ s and $t_{f40} = 2.816$ s, with the bias persisting until $t_{f40} = 5.632$ s. Despite these deviations, the glider still achieves 20 cm displacement. However, the sinking and floating times are extended (~4.8 s and ~5.6 s, respectively), indicating a lower average vertical velocity and reduced energy-conversion efficiency compared with the midpoint case, consistent with prior findings that glider energy consumption and motion effectiveness are tightly coupled [18],[40]. The persistent pitch bias suggests that part of the buoyancy actuation is diverted to attitude correction rather than producing direct vertical displacement. This aligns with the broader understanding that pitch dynamics dominate underwater-glider vertical behavior and require regulation to maintain stable, efficient trajectories [41],[42].

The most forward ballast configuration, shown in Fig. 6, places the ballast at $\lambda_b = 0.2$. This case highlights the destabilizing influence of excessive forward placement. The sinking sequence begins at $t_{s20} = 0$ s with a steep nose-down posture that grows more pronounced at $t_{s20} = 1.038$ s and $t_{s20} = 2.076$ s, remaining locked through $t_{s20} = 4.152$ s. The floating sequence follows the opposite pattern: a strong nose-up tilt is present

at $t_{f20}=0$ s and persists through the entire motion up to $t_{f20}= 5.052$ s. These extreme orientations reduce the vertical displacement to only 15 cm, while the sinking and floating times exceed beyond 4.1 s and 5.0 s respectively. As a result, both velocity and energy-conversion efficiency are significantly degraded, consistent with prior work linking underwater-glider energy consumption to motion effectiveness [18],[41],[42].

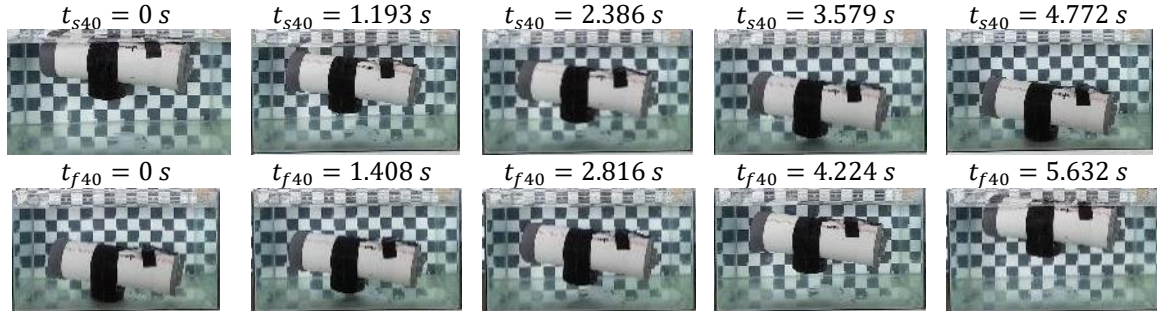


Figure 5. Sequential sinking (top row) and floating (bottom row) motions of the underwater glider with ballast position ratio $\lambda_b = 0.4$

These results emphasize the critical role of time-dependent orientation in determining performance. At $\lambda_b = 0.5$, stable posture from the start leads to symmetric and efficient ascent and descent. At $\lambda_b = 0.4$, modest pitch errors lengthen travel time but still allow full displacement. At $\lambda_b = 0.2$, steep initial misalignments dominate, yielding incomplete displacement and poor efficiency. Two main findings emerge: early orientation within the first second strongly determines overall energy-conversion efficiency and sinking–floating trajectories become more symmetric as ballast approaches the midpoint, confirming that balanced mass distribution is central to reliable buoyancy-driven glider operation [41],[43].

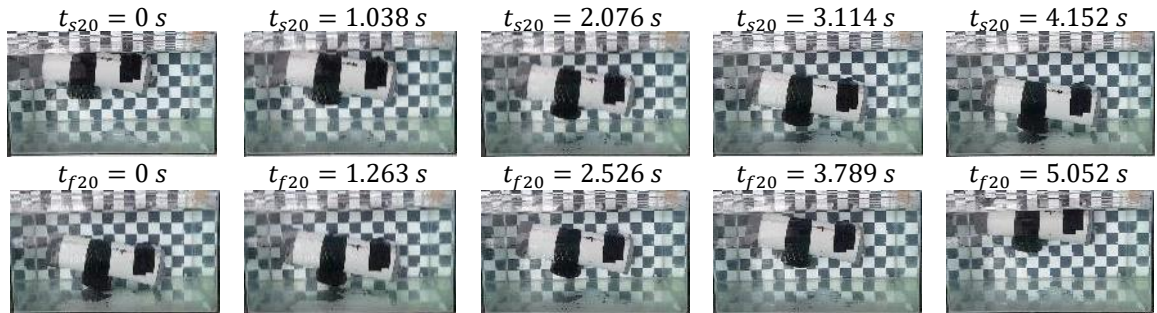


Figure 6. Sequential sinking (top row) and floating (bottom row) motions of the underwater glider with ballast position ratio $\lambda_b = 0.2$

Fig. 7 illustrates the effect of ballast position ratio (λ_b) on the average vertical velocity (v_{avg}) of the underwater glider under both sinking (negative buoyancy) and floating (positive buoyancy). The results demonstrate a clear upward trend: as the ballast shifts from the forward position ($\lambda_b = 0.2$) toward the midpoint ($\lambda_b = 0.5$), velocity increases in both buoyancy states. At $\lambda_b = 0.2$, the glider achieves modest sinking and floating velocities of about 0.034 m/s and 0.028 m/s, respectively. By contrast, at $\lambda_b = 0.5$, the maximum velocity reaches ~ 0.045 m/s. This improvement reflects the stabilizing effect of rearward ballast placement, which reduces pitch oscillations and enables the buoyancy-driven actuation to translate more effectively into net vertical displacement [32,41,42]. Across all ratios, negative buoyancy yields slightly higher vertical velocities than positive buoyancy because descent is assisted by the vehicle weight, whereas ascent must overcome hydrodynamic drag while generating upward motion [30,33]. Notably, the velocity difference between descent and ascent becomes smaller at $\lambda_b = 0.5$, suggesting that near-midpoint ballast placement better balances the ascent–descent dynamics and promotes a more symmetric vertical trajectory [30],[32],[41].

Fig. 8 shows buoyancy-driven energy-conversion efficiency (η), defined as the ratio of useful mechanical power from buoyancy-driven motion to the electrical input supplied to the buoyancy engine. The pattern closely parallels that of velocity: efficiency increases with ballast shifted aft. At $\lambda_b = 0.2$, efficiency is low, 15.5% for sinking and 12.8% for floating, reflecting energy wasted on unstable orientations. At $\lambda_b = 0.4$, values improve to $\sim 17.8\%$ and 16% , respectively. The highest efficiencies occur at $\lambda_b = 0.5$, reaching $\sim 23\%$ during sinking and $\sim 22.5\%$ during floating. While negative buoyancy retains a slight advantage at lower ratios due to gravitational stabilization, this benefit diminishes as the ballast approaches the midpoint, where performance in both buoyancy states converges.

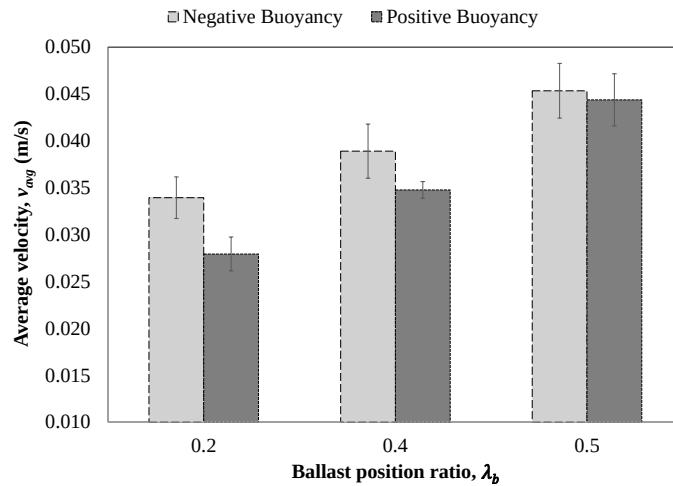


Figure 7. Average vertical velocity of the glider under negative and positive buoyancy at different ballast position ratios

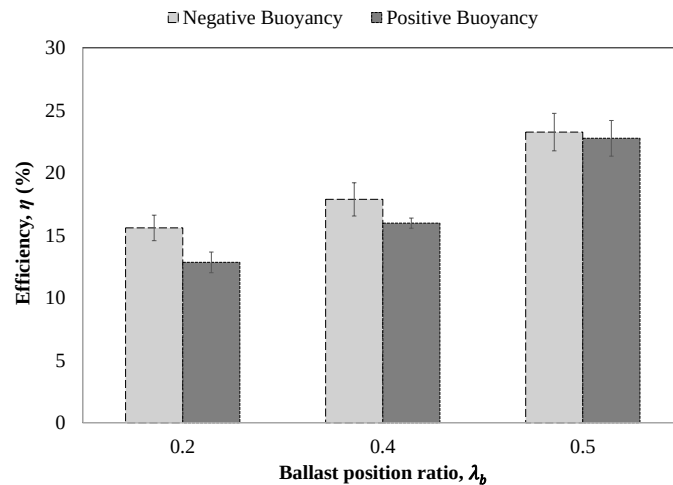


Figure 8. Buoyancy-driven energy-conversion efficiency of vertical displacement under negative and positive buoyancy at different ballast position ratios

The velocity and efficiency results highlight the central role of ballast placement in governing glider performance, consistent with prior studies [18],[26],[40]. At $\lambda_b = 0.2$, forward ballast induces steep pitching and unstable motion, limiting both speed and efficiency. Moving the ballast aft to $\lambda_b = 0.4$ improves performance, but residual misalignment remains. The midpoint configuration ($\lambda_b = 0.5$) delivers the best results, maximizing vertical velocity and efficiency while equalizing sinking and floating behavior. For buoyancy-driven gliders, which rely solely on density changes without thrust, these findings are especially significant. The findings show that careful tuning of ballast distribution, through its impact on attitude dynamics, plays a critical role in achieving stable and efficient vertical-plane motion, beyond changing buoyancy magnitude alone [30],[41],[42]. Optimizing ballast placement around the midpoint can improve energy-motion performance and reduce motion errors, which are directly linked to endurance and maneuvering precision in underwater-glider operations and design [18],[20],[40].

Table 1 summarizes the average pitch and roll values recorded by the MPU6050 sensor during the sinking and floating phases of the glider. These results highlight how ballast placement influences orientation and, in turn, vertical motion efficiency. Pitch shows the strongest dependence on ballast ratio. At $\lambda_b = 0.2$, the glider exhibits steep nose-down angles of 103.73° during sinking and 102.44° during floating. Such excessive inclinations push the vehicle far beyond neutral, leading to inefficient vertical motion and greater resistance, in general, due to adverse flow conditions and increased losses, as commonly observed in CFD-based flow analyses under altered orientations/geometries [44],[45].

When the ballast is shifted rearward to $\lambda_b = 0.4$, pitch angles reduce to about 97° for both buoyancy states, indicating improved stability and less extreme nose-down orientation. The small difference between sinking and floating here suggests that placing ballast near the mid-body enables more consistent pitch control. At $\lambda_b = 0.5$, pitch stabilizes further, with values of 85.75° (negative buoyancy) and 87.76° (positive buoyancy). This near-vertical alignment is optimal, minimizing wasted energy and ensuring that buoyancy forces translate efficiently into vertical displacement. Roll values, in contrast, remain relatively stable across all ballast ratios. At $\lambda_b = 0.2$, roll averages around $87\text{--}88^\circ$, while at $\lambda_b = 0.4$ it remains similar under sinking but decreases slightly under floating (85.74°). At $\lambda_b = 0.5$, roll converges again near 86° . The limited variation, within $2\text{--}3^\circ$, indicates that lateral stability is largely unaffected by ballast placement. This consistency confirms that pitch dynamics, rather than roll, are the primary factor influencing performance.

Table 1. Average pitch and roll angles of the glider at different ballast position ratios under negative and positive buoyancy states

Ballast position ratio, λ_b	Buoyancy state	Average pitch ($^\circ$)	Average roll ($^\circ$)
0.2	Negative	103.73 ± 0.69	87.23 ± 0.85
	Positive	102.44 ± 0.78	88.24 ± 0.83
0.4	Negative	97.26 ± 0.94	87.25 ± 0.86
	Positive	97.23 ± 0.89	85.74 ± 0.56
0.5	Negative	85.75 ± 1.26	86.23 ± 0.83
	Positive	87.76 ± 1.29	86.24 ± 1.43

The results demonstrate that ballast placement plays a decisive role in governing the vertical performance of buoyancy-driven underwater gliders, in agreement with the literature [32],[42]. Forward ballast ($\lambda_b = 0.2$) produces steep pitch angles, unstable trajectories, reduced vertical displacement, and the lowest velocity and energy-conversion efficiency. Shifting the ballast slightly aft ($\lambda_b = 0.4$) moderates these effects, allowing full displacement but with longer travel times and modest energy losses. The most balanced configuration occurs at the midpoint ($\lambda_b = 0.5$), where the glider maintains near-vertical orientation, achieves symmetric sinking and floating trajectories, and delivers the highest velocity and efficiency. Roll remains relatively stable across all cases, confirming that pitch stabilization is the dominant factor in performance. These findings highlight the broader design implication that careful mass distribution is central to efficient buoyancy-driven motion. Placing the ballast near the mid-body of the glider ensures stable orientation, minimizes energy loss and enhances endurance, consistent with broader fluid-resistance design principles showing that reducing drag-related losses improves energy efficiency and operational range [46], offering a practical guideline for future prototype development and long-duration underwater missions.

Conclusion

This study addressed the limited experimental evidence on longitudinal mass distribution effects in laboratory-scale buoyancy-driven gliders by testing a 50 cm prototype equipped with a syringe-based buoyancy engine. The results consistently show that ballast position governs the dynamic response of the glider primarily through pitch behavior. A forward ballast location ($\lambda_b = 0.2$) produced extreme pitch angles ($>100^\circ$), limited the vertical displacement to 15 cm, and resulted in the lowest buoyancy-driven energy-conversion efficiency ($\sim 13\text{--}15\%$). Shifting the ballast aft ($\lambda_b = 0.4$) restored full displacement and improved stability; however, residual pitch deviations increased travel time and constrained efficiency improvements. The midpoint configuration ($\lambda_b = 0.5$) delivered the most balanced performance, maintaining near-vertical alignment, yielding more symmetric sinking and floating trajectories, achieving the highest velocity (~ 0.045 m/s), and reaching peak buoyancy-driven energy-conversion efficiency ($\sim 23\%$). Roll varied only slightly across cases, confirming that pitch dynamics dominate vertical performance. Overall, the findings indicate that simple ballast tuning near the mid-body can substantially improve stability and buoyancy-driven energy-conversion efficiency in small gliders, providing a practical design guideline for shallow-water or coastal applications without redesigning the buoyancy engine. Because the experiments were conducted in a controlled tank using a scaled prototype, future work should validate these trends under field conditions and in larger platforms, supported by hydrodynamic modeling and active control strategies that couple buoyancy regulation with adaptive mass distribution.

CRedit authorship

Arie Sukma Jaya: Conceptualization, Methodology, Supervision, Validation, Writing – Review & Editing. **Yusuf Arindyatama Putra:** Investigation, Data Curation, Formal Analysis, Writing – Original Draft.

Declaration of Competing Interest

The authors declare no competing interests.

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