

ALBATROSS: A bio-inspired, aerially deployable, autonomous sailing sensor platform

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Rapid deployment of autonomous sensor platforms in remote aquatic areas remains a challenge for environmental monitoring, disaster response, and ocean science. We present ALBATROSS (Airborne Lander with Buoyant AuToROtating Sailing Sensor), a hybrid bio-inspired robot that passively autorotates for soft water landing and transitions into a wind-driven sailboat. Its dual-function rigid wingsails, acting as both sails and autorotating wings, enable efficient descent and propulsion. A freely rotating main sail, controlled by a tail rudder, and a directly actuated front sail enhance thrust and aerodynamic stability. A biomimetic caudal fin-inspired rudder enables propulsion during low-wind conditions and agile maneuvering in challenging upwind tacking. We empirically evaluated different wingsail airfoils through wind tunnel testing and optimized rudder design through hydrodynamic modeling, material selection, and speed–power efficiency analysis across different sizes and stiffnesses. Field experiments validate aerial deployment from 150 meters, autorotating descent, passive self-righting, and successful waypoint navigation using both rule-based control and a reinforcement learning approach. By integrating minimal actuation, bio-inspired structures, and passive dynamics across aerial and marine operating regimes, this work extracts generalizable design principles for lightweight, aerially deployable sailing robots capable of robust, energy-efficient marine sensing.

One-sentence summary: A bio-inspired robot passively autorotates from aerial deployment to become an autonomous sailboat for marine sensing.

INTRODUCTION

Marine sensing has become increasingly important for environmental monitoring, oceanographic observation, and maritime operations (1–4). Surface-based sensing is widely used for early detection of harmful marine biohazards such as algal blooms (5, 6), debris tracking (7, 8), marine wildlife monitoring (9, 10), and human activity surveillance to promote sustainable fishing and maritime operations (11). In many of these applications, rapid deployment of sensing assets is critical, particularly in response to time-sensitive events such as typhoons, underwater earthquakes, oil spills, and chemical leaks.

Marine surface sensor platforms typically take the form of buoys (12, 13) or robotic boats (14, 15), often powered by solar energy and equipped with communication systems and basic locomotion. Robotic sailboats, in particular, are well suited for long-duration marine exploration due to their low energy demands and ability to exploit ambient wind for propulsion (16, 17). Existing designs range from soft-sail platforms (18, 19) to rigid wing-sail systems (20, 21), with control approaches spanning passive rotation (22), motorized actuation (23), dual-sail configurations with rudderless steering (24), and autonomous sailing controllers (25, 26).

Commercial systems such as Saildrone (27) and Sailbuoy (28) have demonstrated reliable performance in oceanographic missions. However, these platforms are relatively large, costly, and require manual deployment from ships or shore. Their responsiveness is inherently constrained by logistical factors such as launch timing, weather conditions, and transit speed. As a result, although sailing platforms excel at persistent operation, they are poorly suited for rapid insertion into remote or dynamically evolving environments.

Hybrid aerial–marine robots aim to combine the rapid mobility of aerial systems with the environmental reach of aquatic platforms. Waterproof quadrotors (29–31) rely on sealed electronics and reuse aerial propulsion for underwater maneuvering, whereas fixed-wing systems (32–34) typically incorporate foldable wings, additional thrusters, ballast systems, and reconfigurable structures to transition between flight and submerged modes. Fixed-wing UAVs that land and operate on water without submerging have also been explored for surface-level sensing (35), with delta-wing aerial–aquatic designs offering mechanically simpler alternatives (36). SailMAV (37), for example, can transform from fixed-wing into a sailboat for extended surface missions.

In general, hybrid aerial–aquatic systems must juggle two fundamentally different modes of mobility, often requiring multiple actuators, sensors, and mechanical transitions. This added complexity increases system mass and power consumption, limits endurance, and reduces available payload capacity for sensing. Moreover, many such systems still rely on shore- or ship-based deployment and have limited operational range, restricting their effectiveness in time-critical marine sensing scenarios.

Aerial deployment offers a complementary capability by enabling fast insertion of sensing platforms without reliance on surface infrastructure. Manned aircraft can release sensors from high altitudes (38–40), but payloads must be ruggedized to survive impact, often making them bulky and costly (41). Smaller and lighter sensors reduce impact forces but typically trade off durability (42, 43). More recently, Uncrewed Aerial Vehicles (UAVs) have been explored as sensor

platforms themselves (44), enabling controlled release and self-navigation. Bio-inspired designs have demonstrated passive descent mechanisms, including origami-inspired gliders (45) and maple seed-inspired autorotating systems (46, 47). These approaches are mechanically simple and robust, and more advanced designs allow controlled directional descent (38), including our previous samara-inspired, single-actuator systems capable of guided autorotation (48–50). However, existing systems focus primarily on aerial-to-ground deployment and remain unsuitable for sustained operation in marine environments.

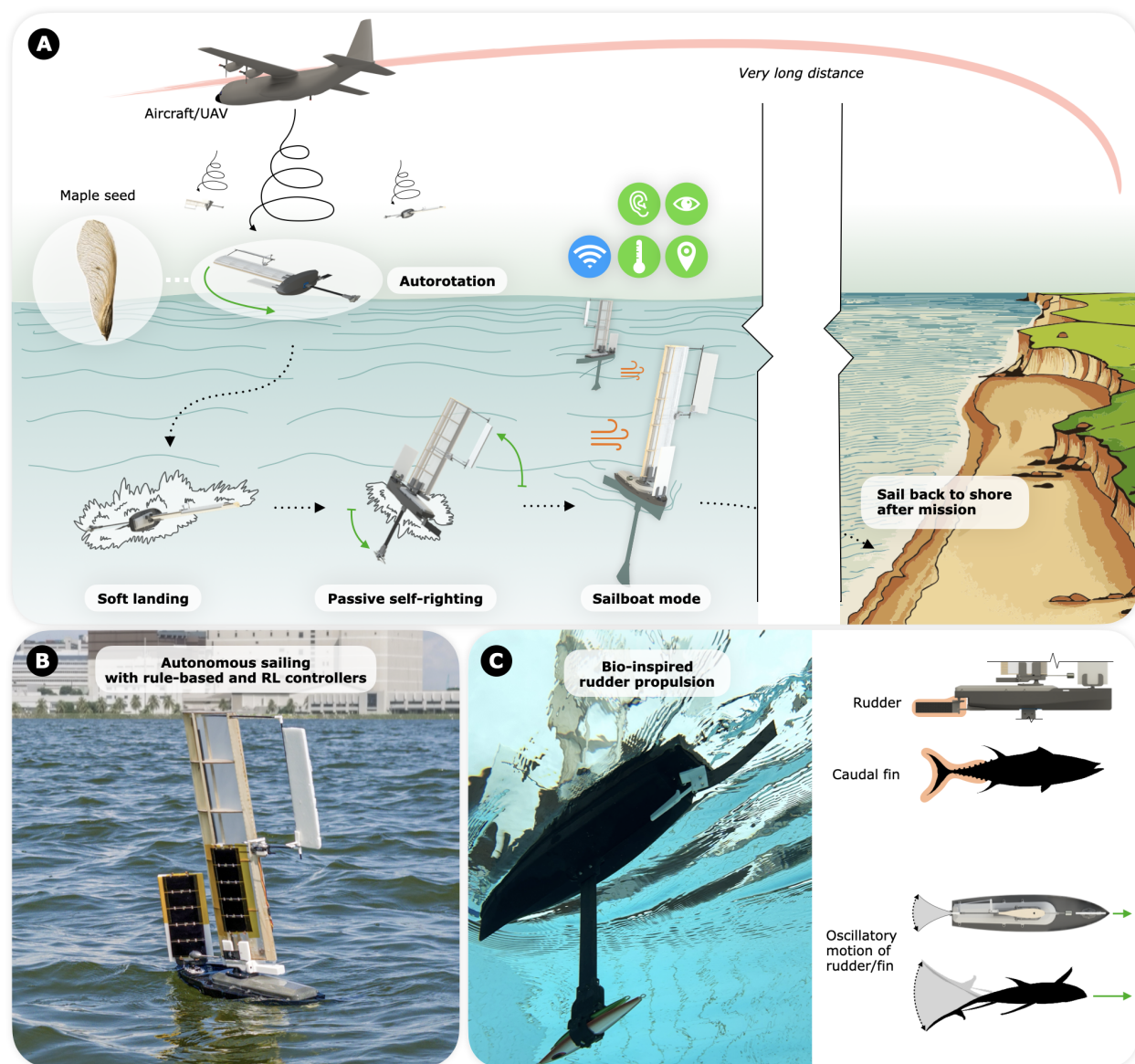


Figure 1: Nature-inspired aerial deployment, autonomous sailing and biomimetic secondary propulsion. (A) Our hybrid platform, ALBATROSS, is intended for deployment from crewed or uncrewed aircraft. Upon release, it enters autorotation for a controlled, low-impact water landing. It passively self-rights due to its weight distribution and begins operation as a sailboat. (B) ALBATROSS autonomously sailing at a local reservoir. (C) Underwater picture showing the biomimetic rudder in action. The long and narrow rudder oscillates to provide active thrust and enhance maneuverability similar to caudal fin of fish.

There is a demonstrated need for rapid-response ocean observing, such as hurricanes, that is already addressed using aircraft-deployed instruments (51, 52). Many emergency marine monitoring contexts are time-sensitive, such as in oil-spill response (53). However, aircraft-deployed ocean instruments are typically expendable, and existing surface robotic platforms generally require shore- or vessel-based deployment and transit time to reach the region of interest. This leaves a gap for a rapidly insertable, low-impact, recoverable surface platform that can be delivered by air and then persist via energy-efficient surface locomotion.



Movie 1: Aerial deployment and hybrid operation of ALBATROSS. This video shows the real-world aerial deployment, autorotation and sailing operation of ALBATROSS.

In this article, we introduce ALBATROSS (Airborne Lander with Buoyant AuToROtating Sailing Sensor), a hybrid robotic platform that combines nature-inspired autorotation with autonomous sailing. Building upon prior work on guided autorotation (50), ALBATROSS is designed to be released from an aircraft or UAV, passively enter autorotation for a controlled, low-impact water landing, self-right without actuation, and seamlessly transition into a wind-powered sailboat (Fig. 1A and Movie 1). Unlike many hybrid aerial–marine systems, ALBATROSS eliminates the need for aerial propulsion, complex mechanical reconfiguration, or active stabilization during the air–water transition, and can sail back to shore at the end of a mission. The platform follows a minimalist design philosophy centered on multifunctional structures and passive dynamics (Fig. 1B). Two rigid wingsails serve dual roles as aerodynamic lifting surfaces during descent and as propulsive sails on water. This philosophy extends to a caudal-fin-inspired rudder that oscillates to generate thrust (Fig. 1C), particularly aiding maneuverability in low-wind or upwind conditions. Overall, ALBATROSS achieves autonomous navigation using only three actuators and three primary sensors, reducing system complexity while retaining control authority. In addition to its hardware design, ALBATROSS demonstrates full autonomous sailing using a traditional Rule-Based (RB) controller. A Reinforcement Learning (RL) controller is trained in simulation as a proof-of-concept to assess whether the hybrid aerial–marine dynamics of ALBATROSS are compatible with data-driven control, and its behavior is evaluated alongside the established rule-based approach. We present a complete design and validation framework that extracts generalizable design principles for aerially deployable marine robots, encompassing dynamic modeling, simulation, fabrication, and field testing. In repeated field trials, ALBATROSS was deployed from a

UAV at an altitude of 150 m, where it demonstrated stable autorotation, soft water landing, passive self-righting, and subsequent autonomous navigation between waypoints. Hybrid aerial–marine feasibility was demonstrated using a smaller S-variant (Small), whereas sailing controller performance was evaluated using a geometrically identical but 50% larger L-variant (Large) to enable more systematic testing. Together, these results demonstrate the feasibility of ALBATROSS as a lightweight, energy-efficient platform for aerial insertion and persistent marine surface sensing.

RESULTS

Design Framework and System Architecture

We first describe the design framework and key architectural features of ALBATROSS, as these design choices underpin both the aerial deployment behavior and the subsequent sailing performance evaluated in the following sections. We combined the principles of aerodynamic autorotation and wind-powered propulsion, enabling both aerial and aquatic mobility. This integration was achieved through a set of design principles that emphasize passive dynamics, multifunctional components, and minimal actuation across both aerial and marine operating modes.

ALBATROSS drew design inspiration from modern sailboats and our earlier Samara Autorotating Wing (SAW) systems (48–50). Several key design features enabled the platform’s passive autorotation. The center of gravity (CG) was positioned low, beneath the hull and along the keel, aligning the aerodynamic center of rotation with the keel and promoting both stable autorotation, efficient lift generation and passive self-righting upon water impact. The vertically oriented, lightweight rigid wingsail was rigidly coupled to the keel, ensuring that the primary lift-generating surface and the main structural mass acted as a single integrated unit. Inspired by the fixed-leading-edge and actuated-trailing-edge architecture of the SAW, ALBATROSS employed a two-surface sail configuration consisting of a front sail and a main sail. The front sail functioned as a neutral leading-edge element that promoted stable and repeatable entry into autorotation, whereas the main sail provided the primary lift generation and control authority. Although the front sail was mechanically actuated, its angle was held fixed during autorotation to maintain a neutral aerodynamic bias and enhance rotational stability. Finally, a compact, lightweight hull provided the required buoyancy as its slender form reduces aerodynamic drag during descent.

The overall design of ALBATROSS is shown in Fig. 2A and dimensions are listed in table S1. It was deliberately minimalist, using only three actuators: one for the tail vane, one for the front sail, and one for the boat rudder. Navigation was achieved using three sensors: a GPS module, a compass on the main hull (for boat heading), and a compass on the main sail (for sail angle and inferred wind direction). The system was split into two wirelessly-connected, electrically-isolated subsystems: one in the main hull (handling front sail and boat rudder), and one in the main sail (handling tail vane control).

Beyond aerodynamic considerations, the hull and internal structure were designed to support low-drag marine operation, impact robustness during water entry, and sufficient buoyancy. The hull featured a long, narrow monohull design, intended to minimize both aerodynamic and hydro-

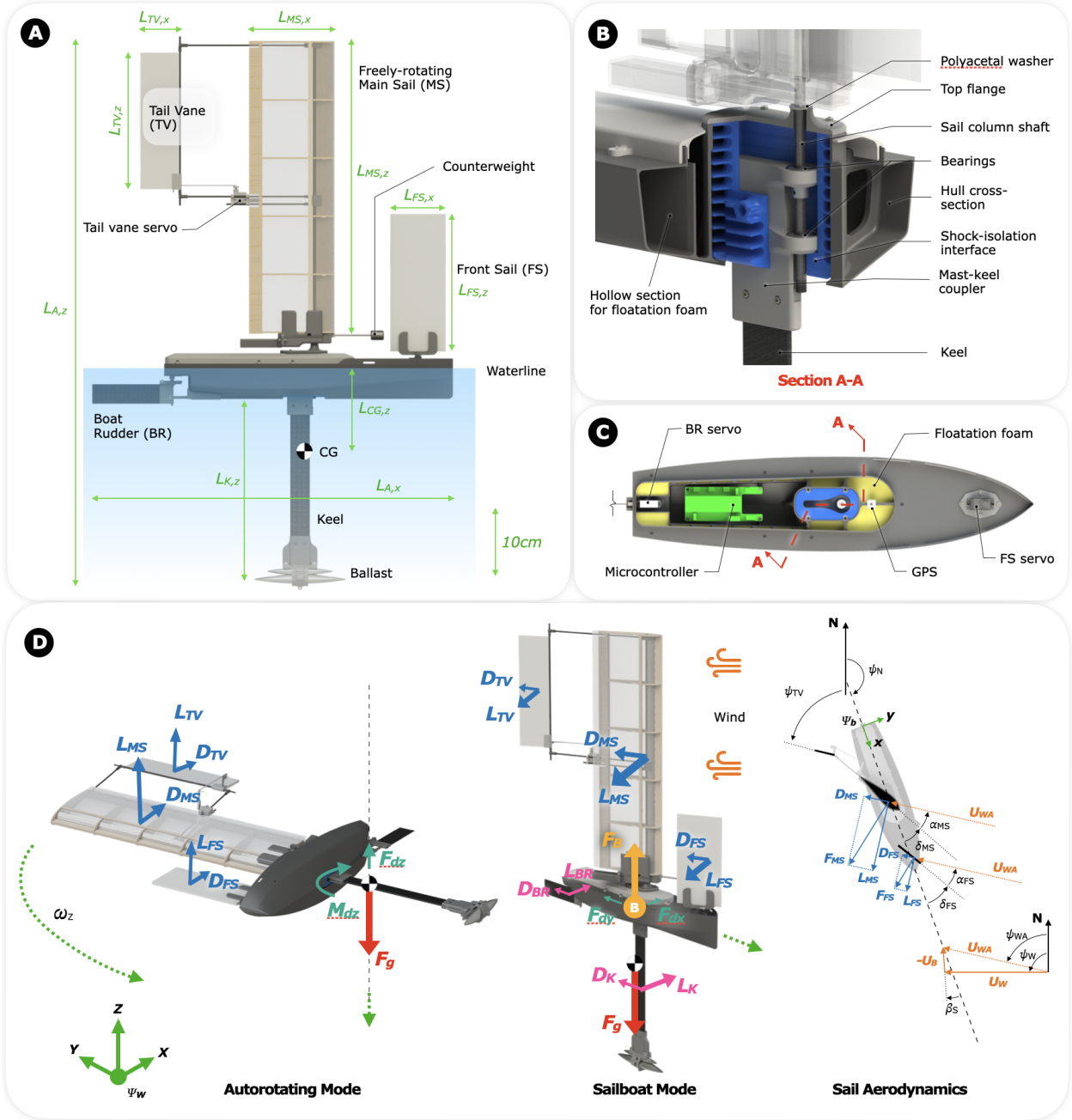


Figure 2: Overview of ALBATROSS design, components and its free body diagram. (A) The key components that make up the ALBATROSS design are shown here, including key dimensions, the waterline, and the approximate location of the center of gravity (CG). Scale bar represents 10 cm. (B) A section view (section line drawn in panel (C)) of the hull, highlighting its internal components. The main sail and keel are connected by a rigid mast-keel coupler, with the sail column shaft supported by bearings. This coupler is isolated from the rest of the hull by a soft shock-isolation interface. (C) A top-down view of the hull without its deck covers and sail structures. A large portion of the hull is filled with floatation foam. (D) The free-body diagram of the platform in both modes of operation, showing the forces and moments acting on the platform. Sail aerodynamics diagram shows wind U_W , apparent wind U_{WA} , boat velocity U_B vectors and angle of attack of the sails and the respective forces produced by the sails.

dynamic drag and enhance directional stability. Compared to multihulls, monohulls are generally lighter and better suited for self-righting designs. The hull's size and volume were small to ensure it provided adequate displacement for buoyancy without generating excessive drag during autorotation. To support rapid prototyping and testing of the design, the hull was fabricated using 3D printing and its design details are shown in fig. S1.

Protecting the thin hull during impact, a vertically aligned cavity housed a custom shock-isolation interface. This interface, made of 3D-printed thermoplastic polyurethane (TPU), mechanically decoupled the heavy keel from the thin hull. It supported a rigid mast-keel coupler that linked the wingsail mast to the keel (Fig. 2B). The keel itself was a flat carbon rod while the main sail rotated freely on a 5-mm carbon shaft held in place with sealed bearings inside the mast-keel coupler.

To further ensure buoyancy and mitigate the risk of waterlogging, the hull was compartmentalized, with floatation foam filling approximately 70% of its internal volume, as shown in Fig. 2C and fig. S1. This foam was made from a two-part expanding polyethylene material that was both lightweight and waterproof, offering high buoyancy even in the event of small cracks from impact.

The sails on ALBATROSS were integral to both its autorotation and sailboat functions. Rigid wingsails were used to generate lift as wings during aerial descent and as conventional sails for propulsion in sailboat mode.

The main sail, being larger of the two, was designed to catch as much wind as possible in sailing with a lightweight construction to enable a low CG for the platform. The main sail generated most of the thrust required in sailing mode, hence the careful selection of its airfoil is presented in Materials and Methods. Rather than using a large, high power actuator for direct control, the main sail was freely rotating and controlled by a tail vane that regulated its angle of attack indirectly (Fig. 2D). This configuration, also known as self-trimming wing, not only reduces energy consumption for its adjustment and position keeping, but also is passively stable by maintaining a fixed angle of attack in changing wind directions (54, 55). The tail vane was actuated by a small servo mounted directly on the main sail. The axis of rotation for the main sail passed through the airfoil's quarter-chord location, which is the point where aerodynamic lift and drag forces were assumed to be in place. Hence, the forces generated by the main sail would have minimal interference to the tail vane in its control. A small counterweight was added in front of the main sail to balance the weight about its rotation axis.

The front sail, which is a secondary sail, was smaller than the main sail and was actuated directly by a servo. In autorotation mode, it maintained a fixed neutral angle of attack, performing the same stabilizing role as the fixed leading-edge element in our prior Samara Autorotating Wing (SAW) platforms (50). In sailboat mode, it increased the overall sailing force and shifted the center of sailing force forward, enhancing control stability. A servo with 180-degree actuation range was used, with the axis of rotation positioned at the center of the airfoil. For optimal autorotation stability and glide control, wind-tunnel-validated design rules from our earlier SAW work indicated that the front sail area should be approximately $0.5\times$ the main sail area. However, because the main sail rotated freely through 360° , the front sail was geometrically constrained by its close proximity to the counterweight and tail-vane assembly. Its final dimensions (chord = 85 mm, span

= 200 mm) were therefore chosen to eliminate any risk of physical interference while still providing sufficient forward shift of the center of pressure for stable sailing. A flat-plate airfoil was used for its palindromic symmetry, ensuring consistent aerodynamic behavior regardless of airflow direction.

To steer on water, ALBATROSS was equipped with a single underwater rudder, actuated by its third and final servo. Although conventional sailboats rely entirely on wind for propulsion, early field tests in local reservoirs revealed long periods of low or no wind, which limited mobility. Moreover, small-scale sailboats such as ALBATROSS often lacked sufficient momentum to complete upwind tacking maneuvers (56).

To address this, we introduced a secondary propulsion mechanism by repurposing the rudder into a dual-function device, making it capable of both steering and thrust generation. Inspired by caudal fin propulsion in fish, the rudder oscillated laterally like a fish tail, providing thrust as well as steering. This form of biomimetic thrust has been demonstrated in both surface and underwater robots (57–59), often leveraging on compliant fin dynamics.

ALBATROSS’s rudder used a hybrid rigid-compliant design. A rigid front segment was directly actuated by a servo, whereas a compliant rear segment passively flexed during oscillation. This configuration enabled thrust generation without compromising control authority. The compliant material and geometric parameters were tuned to ensure optimal amplitude and frequency response for thrust, as detailed in the Materials and Methods section and the Supplementary Materials. The selected configuration of rudder was long and narrow (30 mm × 125 mm), with the front portion consisting of a rigid 3D-printed structure and the rear portion consisting of a thin flexible carbon fiber sheet. It was able to generate enough forward thrust to propel the platform at a speed of 0.38 ms⁻¹ with a mean power draw of 2.7 W. This biomimetic rudder’s role was to provide occasional low-speed thrust using an existing actuator rather than to replace a dedicated underwater propeller.

Aerial Deployment and Descent Dynamics

The platform’s capability for aerial deployment and controlled descent was evaluated through a combination of dynamic modeling, simulation, and real-world drop tests. A dynamic model of ALBATROSS during steady autorotation was developed using the formulation in the Supplementary Materials. A six-degree-of-freedom simulation was implemented in MATLAB Simulink to predict the platform’s descent behavior and controllability. To steer during descent, the Tail Vane (TV) was actuated using a cyclic control strategy adapted from (50). The control output δ_{TV} was modulated as follows:

$$\delta_{TV} = \begin{cases} \delta_o + \delta_{amp}, & \text{if } \sin(\theta_z + \lambda_c) > 0 \\ \delta_o - \delta_{amp}, & \text{if } \sin(\theta_z + \lambda_c) < 0 \end{cases} \quad (1)$$

where δ_o and δ_{amp} are baseline and amplitude values ensuring dynamic stability, θ_z is the platform’s current heading, and λ_c is the desired movement direction.

Figure 3A shows the resulting motion of the tail vane and main sail over one autorotation cycle in both world and body frames. The square-wave actuation of the tail vane (solid blue line) led to a sinusoidal response in the main sail (dashed red line). This cyclic actuation indirectly regulated

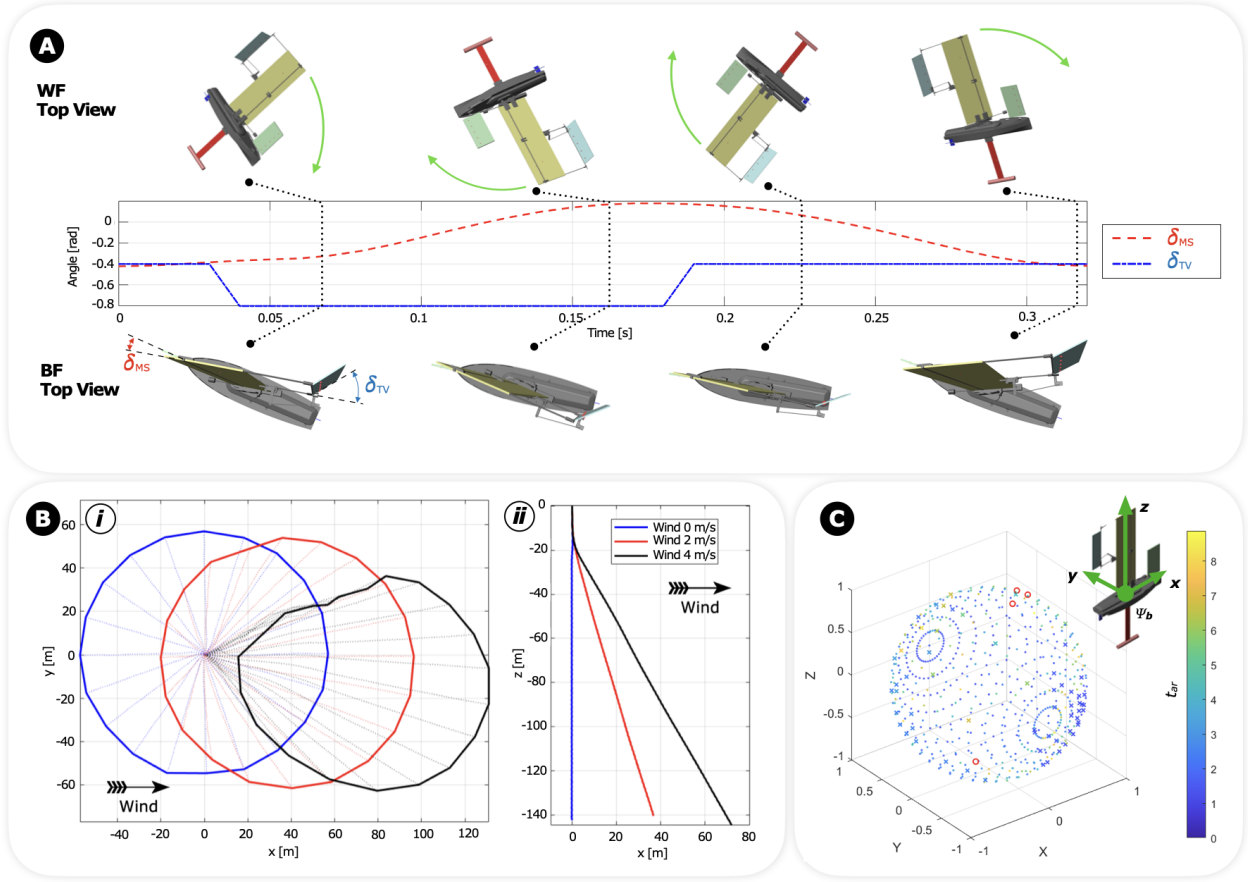


Figure 3: Cyclic actuation and descent dynamics of ALBATROSS. (A) The cyclic actuation of the Main Sail (MS) via actuation of the Tail Vane (TV) in one cycle of rotation, showing views from top view in World Frame (WF) and Body Frame (BF). (B) The glide envelope of ALBATROSS in various wind conditions. (i) The platform's glide range (with cyclic control) from top view in a duration of 20s in 0, 2 and 4 ms^{-1} wind. (ii) Simulation shows how passive glide trajectory (without cyclic control) can change under wind influence from side view. (C) ALBATROSS was simulated to be released from all possible orientations. Each point on the ball represents the initial orientation of z axis of the platform. The color of the point indicates the time to begin autorotation, a dot represents clockwise initial rotation and a cross represents counter-clockwise initial rotation. Red circles indicate the platform took longer than 10s to autorotate.

the angle of attack of the main sail during every cycle of rotation, creating a lift imbalance of the rotor plane, causing it to tilt thereby controlling the platform's glide direction.

To evaluate gliding performance, we conducted simulations of its autorotation from a 140 m altitude, both with and without wind (see Fig. 3B and movie S1). First, with wind disturbance turned off and cyclic control active, the platform was simulated moving in 20 different directions at equal intervals. The resulting glide envelope, represented by the blue region, was circular, demonstrating the platform's consistent ability to perform a controlled glide in all directions. Next, wind disturbance was introduced, and the same experiment was repeated for wind speeds of 2 ms^{-1} (red) and 4 ms^{-1} (black). A recorded wind data set was used in the simulations, hence wind speed and direction variances were realistically accounted for. As expected, the glide envelope began to bias along the wind direction and becomes noticeably narrower at higher wind speeds. The plot

of x versus z further illustrates how wind influenced the flight trajectory when cyclic control was turned off. In particular, at 4 ms^{-1} wind, the trajectory was substantially affected, deviating by approximately 70 m. In the absence of wind, the measured effective glide ratio was approximately 0.44. In 4 m s^{-1} wind, the platform could exploit wind-induced drift to increase the effective glide ratio to about 1.03. The platform could approximately maintain its horizontal position for wind speeds up to 3.5 m s^{-1} , beyond which downwind drift becomes dominant. These findings highlight the substantial influence of wind on the platform's descent trajectories.

Robustness to initial orientation was assessed by simulating drops from all possible orientations, achieved by rotating the platform's initial release pose about its x and y axes in 10-degree increments. This is represented by a unit sphere in Fig. 3C where each point represents the initial orientation of the z -axis of the platform. For instance, the point at (0,0,1) represents the platform at full upright orientation. The simulation results showed that the platform could successfully enter autorotation from all orientations. t_{ar} is defined as the time taken from release to the onset of autorotation, which is defined as the time when the rotation rate exceeds 15 rads^{-1} . The tail vane was set at a constant δ_{TV} of 0.2 rad, which set a bias for the platform to have a stable autorotation in clockwise direction. Certain release angles triggered a brief counter-clockwise spin before flipping over and stabilizing in clockwise. The value of t_{ar} varied but the mode was 1.62 s and the mean was 2.83 s. In some rare cases, t_{ar} could be longer than 10 s. Overall, the simulation results indicated that the platform was highly robust to initial orientation, consistently achieving autorotation within a few seconds of release.

To validate real-life autorotation performance, a prototype (S-variant) was released multiple times from a UAV (DJI Matrice 350) from 150 m altitude using a custom drop mechanism (see Fig. 4 and movie S2). The release was triggered via a radio-controlled linear servo that retracted a string latching mechanism. The descent was tracked via onboard Inertial Measurement Unit (IMU Pesky USFSMAX), barometric altimeter (BMP581), and external cameras (DJI Mavic 3, Nikon P1000, and Insta360 Go 3). Three instrumented aerial drop trials were conducted under slightly different payload configurations, in ambient wind conditions of average 2.45 ms^{-1} as estimated by the deploying UAV. One representative trial is shown here, whereas the remaining two instrumented trials are presented in the Supplementary Materials.

Following release, the descent proceeds through several distinct phases. The platform was initially released in an inverted orientation, as the hoist cable is attached to the keel. It then underwent a brief free-fall phase, during which it tumbled and accelerated to a peak descent velocity of 11.3 ms^{-1} . As airflow developed over the wings, aerodynamic lift was generated, triggering the onset of autorotation. The increasing lift progressively counteracted gravity, leading to a reduction in descent velocity. These initial phases typically occurred within approximately 3 s in our drop trials.

Subsequently, the system entered a steady-state autorotation regime characterized by a constant descent rate of $7.36 \pm 1.72 \text{ ms}^{-1}$ and a rotational speed of $2.75 \pm 0.04 \text{ rev s}^{-1}$, corresponding to a disc loading of 0.96 kg m^{-2} . This phase persisted until water impact. Upon impact, the IMU recorded a peak deceleration of 18.5 m s^{-2} , after which the platform passively self-righted within less than 1 s. Finally, the onboard controller detected the termination of the autorotation phase by identifying a stabilized barometric altitude and the cessation of rapid compass rotations, and

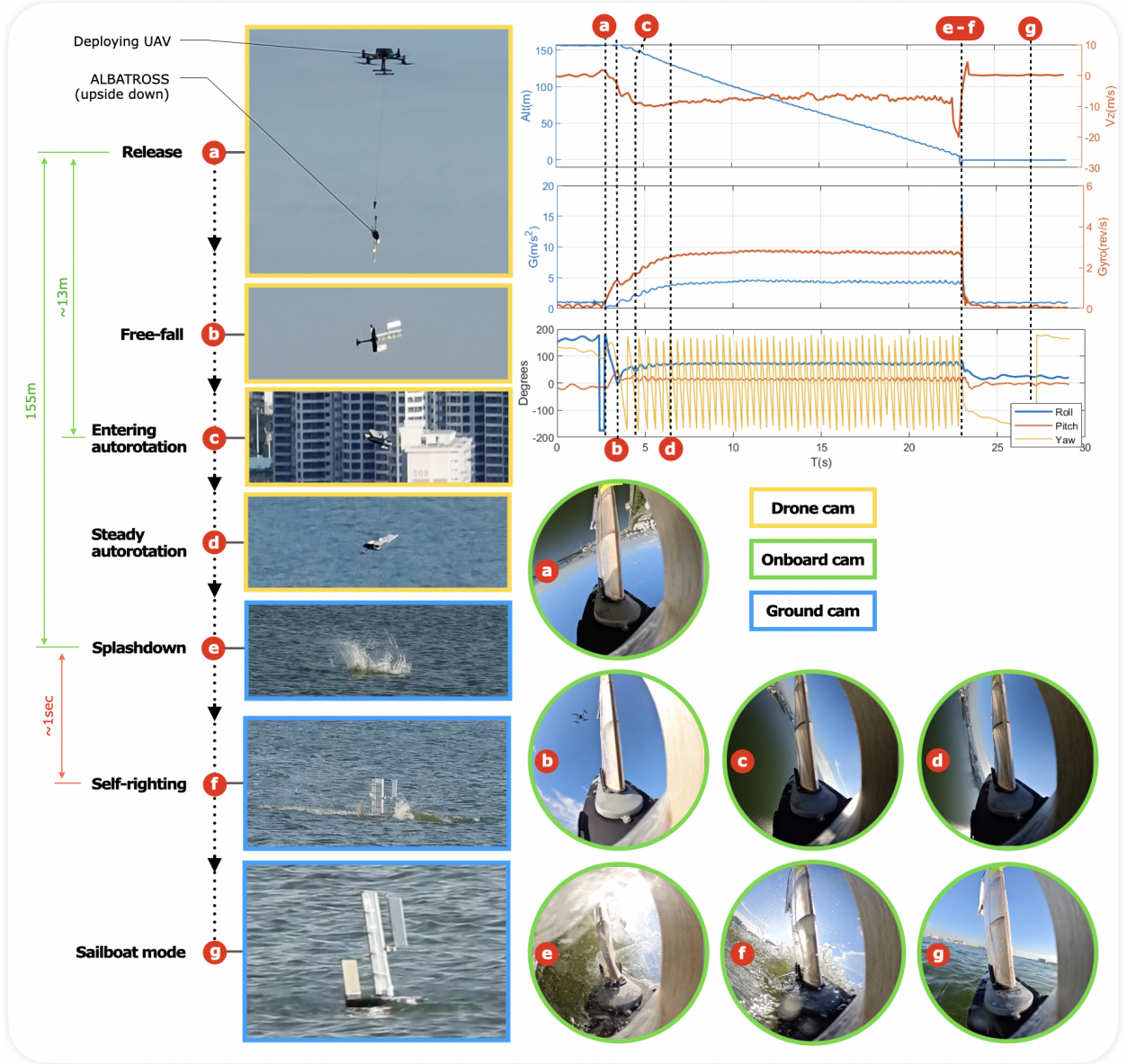


Figure 4: Aerial deployment of ALBATROSS from a UAV. The phases *a* through *g* show the stages from release to water impact and transition into sailboat mode, after ALBATROSS S-variant is released from 150 m altitude, as captured from an aerial camera, an onboard camera, and a ground camera (movie S2). An onboard IMU and barometer captured the angular velocity, acceleration, and altitude data during the descent. The same S-variant prototype was shown undergoing autonomous sailing in movies S3 and S4.

subsequently initiated sailboat mode. Multiple trials were also conducted from 60 m altitude where full sequence of hybrid operation is recorded in movie S3. Aerial deployment and full autorotation were demonstrated in wind speeds up to 4 ms^{-1} in both simulation and experiments. At higher wind speeds, the vehicle should exhibit reduced controllability while remaining passively stable.

The key metrics from all instrumented drop trials are presented in table S7. Two trials converged to a stable autorotative regime with slightly different steady descent and rotation rates that arise from minor configuration variations, whereas the third exhibited a distinct autorotative pose with a higher

descent rate and lower rotation rate, due to a dislodged battery that shifted the CG location. Across the trials, the platform consistently exhibited low-impact water entry and passive self-righting behavior.

For comparison, we estimated the drag-limited descent of a geometrically similar sailboat that is not designed to autorotate. In the absence of autorotation, the platform was expected to fall approximately keel-first due to its low center of gravity and the alignment of dominant drag-producing surfaces, which together placed the center of pressure above the center of mass and promoted a stable vertical orientation during descent. Accounting for aerodynamic drag, the terminal velocity of such a keel-first free fall can be estimated using $v_t = \sqrt{\frac{2mg}{\rho C_D A}}$ where m is the mass of the platform, ρ is the air density (taken as 1.2 kg m^{-3}), C_D is the drag coefficient, and A is the projected cross-sectional area. Using the measured keel-first projected area of the hull ($A = 0.0376 \text{ m}^2$) and adopting a conservative drag coefficient of $C_D = 0.5$ to account for the mildly streamlined hull geometry, the resulting terminal velocity was $v_t \approx 31.0 \text{ m s}^{-1}$. This corresponded to an impact kinetic energy approximately 18.5 times higher than that measured during autorotating descent.

Sailing Performance and Environmental Sensing

To demonstrate sailing performance, ALBATROSS was tested extensively in two local reservoirs in Singapore; Bedok Reservoir (1.340447, 103.923441) and Pandan reservoir (1.318673, 103.739676). Aerial footage of the trials were captured using a DJI Mavic 4 Pro drone (movie S5), whereas onboard data were recorded via the microSD card and transmitted to a ground station in real-time via the RFD900ux radio modem.

Although the S-variant of ALBATROSS was capable of autonomous sailing, its experimental evaluation faced practical challenges due to its compact scale, which limited wave resistance and upwind performance. In Singapore’s characteristically low-wind conditions, boundary-layer effects further reduced effective wind speed at the low sail height. In addition, a support tugboat was required for reliable communication relay between the ground control station and the platform, and minor water ingress occasionally necessitated manual recovery by a separate boat, slowing iterative testing and troubleshooting. To enable more systematic and reliable sailing experiments, we developed the L-variant, which was geometrically identical to the S-variant but uniformly scaled up by 50%, preserving the overall architecture, structural layout, sail configuration, actuator placement, and relative CG location. Accordingly, the sailing controller results presented in this section were obtained using the L-variant.

A RB controller was developed based on traditional sailing techniques (tacking, reaching, gybing) and its algorithm is outlined in the Supplementary Materials. Figure 5A shows an octagon-shaped path sailed by ALBATROSS using the baseline controller. As ALBATROSS sailed from its start point, its path, which turns 45 degrees at each waypoint, gradually changed from port wind, downwind, starboard wind, to upwind. The controller detected the changes in wind direction and adjusted the sail angles in broad reach, beam reach, and close reach sailing. When sharp turns were required, the controller deployed rudder flapping to help execute the turn. When moving

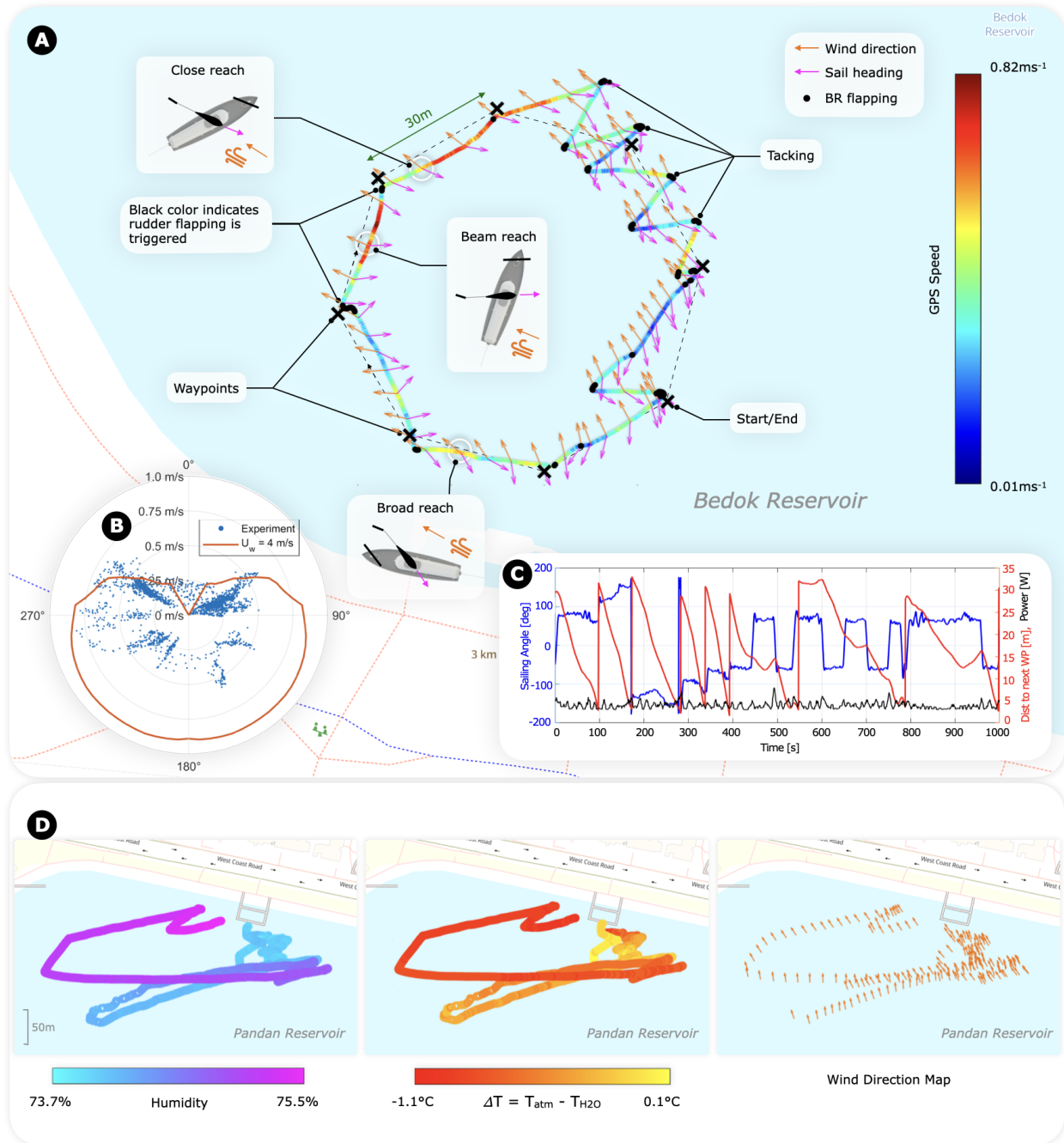


Figure 5: Autonomous sailing experiments at local reservoirs. (A) The trajectory of ALBATROSS L-variant following an octagon-shaped path, with the color indicating its speed. Small arrows, plotted at a constant time interval, indicate the instantaneous wind direction and sail orientation. Black colored parts of its trajectory indicate when rudder flapping was used to execute turning and increase forward thrust. Also shown are how the sails were oriented in close reach, beam reach and broad reach sailing. (B) A polar plot of the ground speed with respect to the apparent wind angle, plotted together with simulated values at $U_w = 4 \text{ ms}^{-1}$. (C) Sailing angle (blue) showing how the platform oriented itself with respect to wind and distance to waypoint (red) over time. Power consumption of the platform is also shown in black. (D) ALBATROSS sailed autonomously for 3 hours while recording environmental data such as humidity, heat flux and wind direction. Data was measured on an overcast day in the evening.

upwind, the controller used tacking maneuvers to advance towards the waypoint. The polar plot in Fig. 5B shows measured ground speed with respect to apparent wind angle, which matches simulation at $U_w = 4 \text{ ms}^{-1}$. A peak speed of 0.82 ms^{-1} was observed in segments with beam reach and close reach sailing. Sailing angle ($\psi_N - \psi_{WA}$) is the angle between the platform's heading and the apparent wind direction, which is shown in blue in Fig. 5C. The platform was able to consistently maintain a close reach angle of approximately 55° and the time between each tack is set at 50 s in this experiment. The distance to waypoint is shown in red, which indicates how far the platform was from its next waypoint. This value was generally decreasing, with occasional increases during tacking maneuvers. The platform exhibited an average power consumption of 3.98 W, with a peak power draw of 7.97 W recorded during a tacking maneuver that relied heavily on rudder oscillation. Notably, the overall power usage remained comparable during upwind and downwind sailing, indicating that active propulsion was employed sparingly and primarily during maneuvering rather than continuous cruising.

A RL controller was also explored as a proof-of-concept. It demonstrated comparable waypoint convergence in simulation and slightly smoother maneuvers in field trials but did not outperform the RB controller and is therefore presented only in the Supplementary Materials.

The platform could operate from wind speeds as low as 0 ms^{-1} , relying primarily on rudder oscillation for locomotion. In experiments, it performed successfully at average wind speeds of 4 ms^{-1} . Due to its freely rotating sail, the platform could handle substantially higher wind speeds: the sail reduced its angle of attack to minimize lateral forces and limit side lean.

In one experiment, the platform sailed autonomously for approximately 3 hours while continuously recording parameters such as humidity and heat flux (Fig. 5D). At the end of this run, the main battery had at 50% charge remaining and the main sail battery had 70% remaining. The environmental measurements are important indicators of air–water exchange processes, as humidity levels near the surface influence evaporation rates whereas surface heat flux governs the transfer of thermal energy between the reservoir and the atmosphere. Together, they provide insights into boundary-layer dynamics that play a key role in weather formation and local microclimates. In addition, ALBATROSS can be used to map spatial variability in wind fields by recording direction and intensity at different locations in the reservoir. Although the scale of the reservoir made it challenging to fully decouple spatial from temporal variations, longer deployments, larger domains and the use of a swarm of platforms could enable more detailed mapping of such gradients. These results demonstrated the platform's potential not only as a robotic proof-of-concept, but also as a scalable tool for environmental sensing in aquatic environments.

DISCUSSION

ALBATROSS' Features

ALBATROSS integrates aerial deployment with energy-efficient aquatic locomotion within a single, passively stabilized system. Its core innovation lies in a dual-function sail architecture, in which the same rigid sails act as autorotating aerodynamic surfaces during descent and transition seamlessly

Table 1: Comparison of hybrid aerial-aquatic vehicles. The table compares the key specifications of various hybrid aerial-aquatic vehicles. n_{act} is the number of actuators, Type is the type of vehicle (FW: fixed-wing, MR: multirotor, MW: mono-wing), Deployment range is the maximum designed rapid deployment range, Long duration deployment indicates whether the platform can be deployed for self-sustained missions, Sensing indicates the type of possible sensing on surface and sub-surface of water, Payload capacity indicates the percentage of total weight usable for payload, Aquatic locomotion indicates the type of locomotion in water, and Capsized indicates whether the platform can recover from a capsized position. (* - estimated)

Hybrid MAVs	n_{act}	Type	Deployment range	Long duration deployment	Sensing	Payload capacity	Aquatic locomotion	Capsized
SailMAV (37)	8	FW	7 km	Possible	Surface	< 5%*	Sailing	Terminal
Dipper (32)	8	FW	5 km	Not possible	Surface + shallow sub	< 5%*	Propulsion	Potentially recoverable
Aerial-aquatic (30) hitchhiking robot	6	MR	< 1 km	Not possible	Surface + shallow sub	< 5%*	Propulsion	Potentially recoverable
ALBATROSS	3	MW	> 100 km	Possible	Surface + shallow sub	< 35%	Sailing	Recoverable

into wind-driven sails once on water. By deliberately minimizing the number of actuators and navigational sensors, the platform has reduced system mass, volume, and power consumption, enabling extended operation under limited energy availability and supporting scalable deployment of low-cost units. Aerial deployment is employed not as a mode of sustained flight, but as a flexible insertion mechanism that enables timely placement of the platform into the region of interest. Release from sufficient altitude allows the platform to converge to a steady autorotation regime prior to water impact, ensuring soft landing and passive self-righting governed by intrinsic aerodynamic and inertial properties rather than active control. Following water entry, ALBATROSS transitions autonomously into a long-endurance sailing sensor platform. To support maneuverability during low-wind conditions and upwind tacking, a caudal-fin-inspired rudder provides intermittent thrust using the same actuator responsible for steering, augmenting wind-driven propulsion without introducing additional dedicated motors. Rather than introducing a new propulsion mechanism, this work explored how multifunctional components and passive dynamics can be deliberately leveraged to minimize actuation while preserving aerial deployability, robustness, and energy-efficient surface mobility. This combination of passive aerial stabilization, minimal actuation, and autonomous surface operation enables rapid deployment of sensing assets over large or remote water bodies, making the platform well suited for applications such as emergency sensor deployment, post-disaster assessment, and environmental monitoring in hard-to-reach regions.

Table 1 situates ALBATROSS within the broader design space of aerial-aquatic robots, highlighting system-level trade-offs rather than direct performance benchmarks. The SailMAV (37) features a similar dual-functionality to our platform, whereby it combines a fixed-wing UAV functionality with an efficient sailboat functionality. The Dipper (32) is a fixed-wing UAV that could sweep its wings backwards for diving into water and uses a single motor to drive both its aerial and aquatic propulsion using clutch mechanism. The aerial-aquatic hitchhiking platform (30) is a multirotor UAV that can operate submerged, and features a bio-inspired suction mechanism to attach itself to objects. These robots carry redundant subsystems for both aerial and aquatic locomotion.

tion, increasing mass, complexity, cost, power consumption, and potential failure points. Designed to be launched from shore or a ship, they are limited in their deployment range and speed. As flight-capable platforms, they are estimated to be able to efficiently carry less than 5% of their total weight as payload, with the weight budget already reduced from redundant subsystems. When capsized, the SailMAV would result in its mission being terminated, as for the other two platforms, recovery may be possible. Compared to these platforms, ALBATROSS is missing the ability to fly after landing. However, owing to this intentional compromise, it has a bigger payload capacity, a welcoming advantage as marine sensors can be typically heavy and bulky. Its rapid deployment range is also substantially larger, as its range now depends on a carrier aircraft. Lastly, due to its passive self-righting capability, ALBATROSS can recover from a capsized position, which is a crucial feature that enables long-term autonomous operations in unpredictable marine environments.

Scalability and Stability

The weight distribution of ALBATROSS is shown in Fig. 6B. To have the CG in its designated location, it requires a hefty counterweight at the keel which takes up 35% of the total weight. This can be replaced by a payload, battery or a heavier sensor in a deployment scenario. Some weight savings can be achieved with the use of molded plastic or carbon fiber hull and lower density floatation foam. For larger payloads, the platform can be scaled up proportionately to increase its buoyancy and payload capacity. Preliminary design assessments suggested that ALBATROSS can be scaled up by approximately 2x its current size without compromising the passive autorotation behavior as seen from our simulation results in Fig. 6C. Beyond this, detailed aerodynamic simulations will be required to better predict descent characteristics. It should be noted that this scalability analysis focused specifically on autorotation dynamics during aerial deployment, as a systematic investigation of sailing performance scalability is beyond the scope of the present study.

The balance between the design of an autorotating glider and that of a sailboat is one that is quite sensitive. On one hand, the glider may perform better in small and lightweight form factor, considering portability and ease of deployment. On the other hand, the sailboat may perform better in a larger form, carrying potentially heavy marine sensing equipment, with a taller sail to catch more wind. A fine balance between the two is required, albeit with a minor compromise on one end, to ensure that the platform is versatile and can be used in a variety of scenarios.

The GZ plot, shown in in Fig. 6D, is a standard naval architecture tool used to assess the static stability of vessels by showing the righting moment arm as a function of heel angle. The larger the righting moment arm, the higher the tendency of the vessel to return to its upright equilibrium. In a typical configuration, a vessel has its CG placed above the Center of Buoyancy (CB), shown in yellow line and emphasized with the dotted yellow line (10x). As the boat heels, the length of GZ increases indicating greater amount of force is rotating the hull back to its upright position. However, once heeled beyond a critical angle, the hull reaches negative GZ where it fails to right itself. Some sailboats may have CG below their CB allowing the hull to have positive GZ throughout all heel angles. In ALBATROSS, its autorotating configuration requires the CG to be intentionally placed well below its CB, resulting in a greater positive righting moment (15.4 times higher at peak

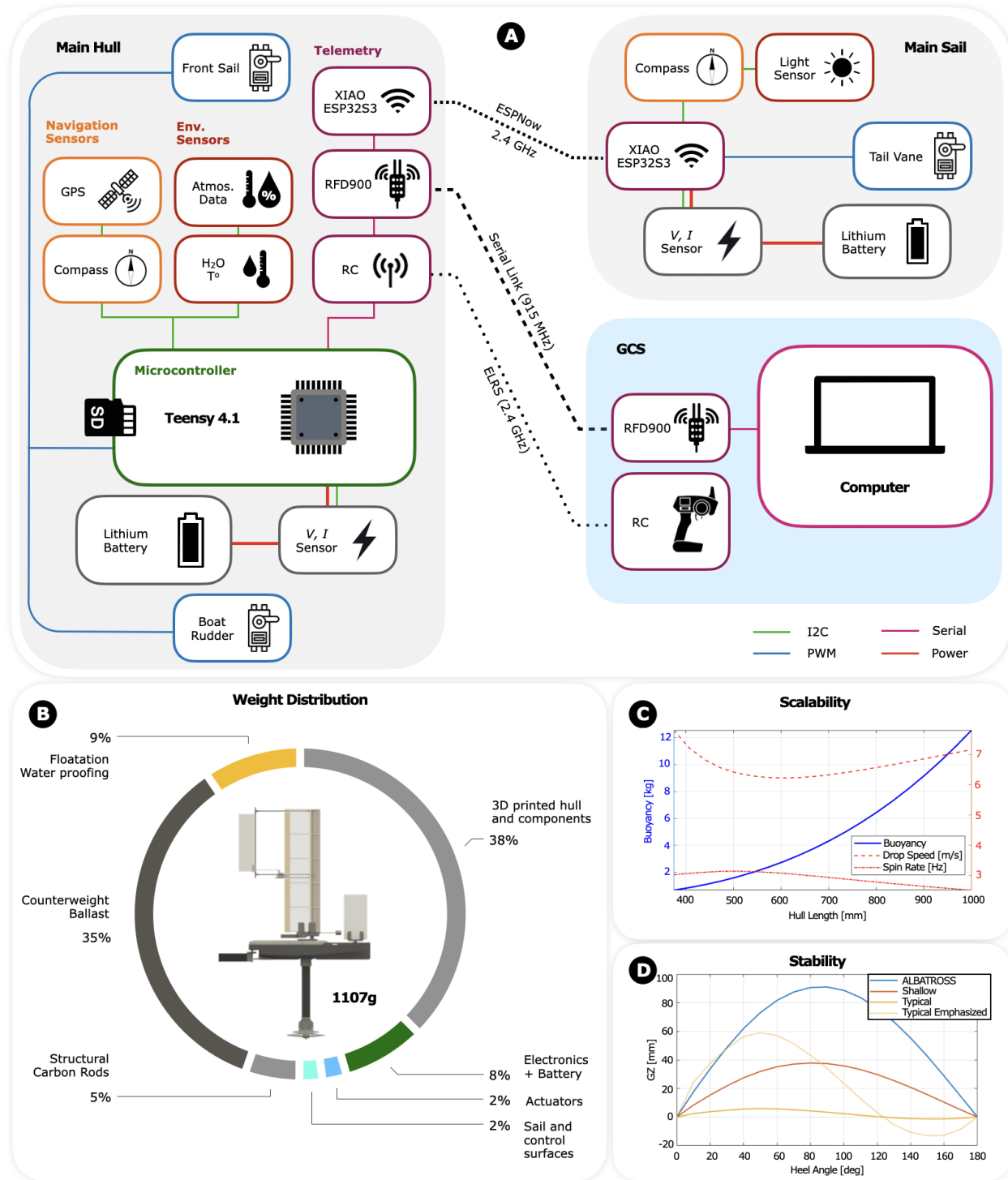


Figure 6: The electrical architecture of ALBATROSS, its weight distribution, scalability and hydrostatic stability. (A) The connections diagram shows how various components such as microcontrollers, sensors, actuators and communication modules are connected on the main hull and main sail subsystems. (B) The weight distribution chart shows how its various components take up the weight budget. The counterweights can be replaced with suitable payload, battery or sensors. (C) Scaling up our simulated model, ALBATROSS is predicted to maintain similar autorotation performance while increasing its buoyancy for larger payloads. (D) The GZ plot shows the current hull design's hydrostatic stability for its current configuration, a shallow keel configuration and a typical sailboat configuration where CG is above CB.

compared to typical) across all heel angles. This configuration ensures that the platform will always passively return to an upright orientation when tilted, a vital characteristic for post-impact recovery and potential long-term autonomous operations in a wide range of environmental conditions. Because this self-righting behavior is governed by hydrostatic stability rather than active control, it is expected to persist under wave-induced disturbances, provided the structural integrity of the platform is maintained.

Generalizable Design Principles

Beyond the specific platform presented, this work highlights a set of generalizable design principles for aurally deployable marine robots operating under strict constraints on actuation, energy, and robustness. First, the deliberate exploitation of passive dynamics, through center-of-gravity placement and aerodynamic coupling, demonstrated how aerial deployment, impact mitigation, and passive self-righting could be unified without active control or mechanical reconfiguration. Second, the use of multifunctional structures and actuators illustrated how mobility across distinct operating regimes could be achieved by reusing components for complementary roles, reducing system complexity while preserving capability. Third, the separation of rapid aerial insertion from sustained flight reframed aerial deployment as a transient delivery mechanism rather than a primary mode of locomotion, enabling access to remote environments without the mass and energy penalties associated with powered flight. Finally, the scalability analysis connected aerial descent behavior and surface mobility, providing insight into how system size mediates trade-offs between deployment robustness and sailing performance. Together, these principles extend beyond ALBATROSS and offer guidance for the design of future hybrid robotic systems that prioritize simplicity, resilience, and energy efficiency across multiple operating domains.

Limitations and Future Work

Although ALBATROSS demonstrated the feasibility of combining passive autorotation with autonomous sailing in a single platform, the current prototypes were developed primarily for concept validation using rapid prototyping techniques. Their small size and lightweight construction made them unsuitable for extended operation in open-ocean conditions characterized by strong currents, high winds, and substantial wave action. Key limitations included a modest glide envelope dictated by the autorotation and sailing design trade-off, reduced upwind performance and wave resistance in the smaller S-variant, and sensitivity of autorotation behavior to center-of-mass shifts.

Future iterations will focus on structural ruggedization, corrosion-resistant materials, and scaling to accommodate ocean-grade sensors and longer-duration missions. Ultimately, ALBATROSS should be viewed as a foundational prototype that establishes a promising modality for rapid, low-cost, aurally deployable marine sensing in remote aquatic environments.

MATERIALS AND METHODS

Fabrication

The hull was fabricated in a single pass using Multi Jet Fusion (MJF) 3D printing, chosen for its low weight, watertight finish, and mechanical integrity. A uniform wall thickness of 1 mm kept the structure lightweight while load-bearing regions were reinforced with thicker walls and support structures. The hull was designed to be printed in a single piece, minimizing assembly complexity and ensuring structural integrity. The hull design was compartmentalized to allow post-print powder removal and to facilitate the insertion of floatation foam. The deck covers were also printed using the same MJF process.

After wires for the front sail servo were routed through a channel in the hull, the hull was filled with floatation foam, which is a two-part expanding polyethylene material. The openings of the foam compartments were closed with laser-cut balsa wood, which prevented the foam from leaking out while curing. The rigidity of the cured foam provided additional structural support to the two lateral sides and the front of the hull.

The Boat Rudder (BR) servo was filled with marine grease to prevent water ingress, as this servo was partially submerged during operation. The BR was made of part 3D-printed rigid portion and part flexible thin carbon fiber sheet which were taped together. The BR was directly mounted to the servo horn using 3D-printed attachments, while the rudder holder underneath ensured the rudder was supported and aligned to its rotation axis, relieving load from the servo arm. A similar mounting mechanism was also used for the front sail which was cut from a flat sheet of foam. The shock-isolation interface, the mast-keel coupler, and the keel were installed into the hull as shown in fig. S1B.

The main sail was fabricated using an assembly of laser-cut balsa wood ribs, spars, and a thin plastic skin. The spars were slotted into the notches of the ribs and glued together using cyanoacrylate adhesive. A long carbon rod was inserted into the quarter-chord location of the main sail to serve as the axis of rotation. Instead of balsa construction, the main sail wing could also be made using hot-wire foam cutting, resulting in a solid foam wing, which is more suitable when building larger sails or wings. Thin pieces of carbon rods and 3D-printed structures were used to mount the tail vane servo. The tail vane, similar to the front sail, was cut from a flat sheet of foam. The tail vane servo drove the tail vane through a servo arm and push rod mechanism.

Marine grease was filled into the gaps between the deck covers and the hull to prevent water ingress. The deck covers were then screwed onto the hull using M2 screws. Deck covers were also glued to the hull using hot glue to ensure a watertight seal.

Electrical Architecture

The electrical system of ALBATROSS was split into two isolated subsystems, with one on the main hull and one embedded in the freely rotating main sail, as shown in Fig. 6A. This separation minimized wiring complexity and preserved rotational freedom.

The main hull housed a Teensy 4.1 microcontroller, which controlled two actuators (front sail and boat rudder), read navigation and environmental sensors, and managed communication and data logging. The main sail carried a lightweight XIAO ESP32S3 (Seeed Studio), which read the

onboard compass and controlled the tail vane. The two subsystems communicated via ESPNow, a low-power peer-to-peer protocol. The main hull transmitted commands to the main sail at 10 Hz, whereas the main sail returned sensor and system data at 5 Hz.

Each subsystem was powered independently. The main hull used a 2S 450 mAh LiPo battery, and the main sail used a 1S 450 mAh LiPo, both monitored by INA219 voltage and current sensors. Navigation relied on three sensors: a GPS unit (MATEKSYS M10Q-5883), and two compasses (MMC5983MA), with one in the hull (20 Hz heading feedback) and one on the main sail. Wind direction was estimated by measuring the relative orientation between main sail and tail vane, eliminating the need for a dedicated wind sensor (details in Supplementary Materials). Actuators included a front sail servo A19DLM (AGFRC), chosen for high torque, waterproofing, and large actuation range ($\pm 90^\circ$), and tail vane and boat rudder servos D05023MG (Blue Arrow), selected for fast response and low weight, enabling effective rudder oscillation.

Environmental sensors equipped on the prototype include a BME280 (air temperature and humidity), DS18B20 (water temperature), and an LTR329 (light intensity). All data, which included sensor readings, actuator states, and control logs, were recorded to an onboard microSD card. Real-time communication with a ground station was handled via an RFD900ux (RFDesign) radio modem. A backup RC controller (ELRS protocol) allowed manual override. The ground station ran a custom MATLAB interface for mission planning, telemetry display, and control tuning.

Control System

The control system of ALBATROSS was designed to operate in two distinct modes: autorotation and sailing. In Autorotation Mode, the tail vane was controlled using a cyclic control strategy, where the angle of attack was modulated based on the platform's heading to tilt the rotation plane and move towards a desired direction. It relied on the passive dynamic stability of autorotation hence it did not require any feedback control. It took the current heading θ_Z from the onboard compass, computed the desired direction λ_c based on current coordinates and target coordinates, and applied the cyclic control law given by Eq. 1 using a Pure Pursuit controller.

Once landed on water, the controller detected the reduced rotation rate and switched to Sailing Mode. Two types of controllers are presented: RB controller and RL controller.

A sailboat moves upwind by tacking, which involves sailing at an angle to the wind direction and alternating sides to progress towards a target. It moves downwind by gybing, which involves turning the stern through the wind. The RB controller used a set of rules to determine the appropriate tail vane angle based on the apparent wind angle, and also determined the desired heading of the boat. The rudder was controlled by a PID controller based on the difference between the desired heading and the current heading. The front sail was simply set to follow the angle of the main sail, such that it generated lift in the same direction as the main sail. The algorithm for the RB controller is detailed in the Supplementary Materials. This algorithm was directly implemented on the onboard microcontroller (Teensy 4.1) and the desired waypoints were sent from the ground station via the RFD900ux radio modem.

We also explored using RL to train an end-to-end control policy for ALBATROSS in sailing

mode. RL enabled an agent to learn control policies from a high-level reward signal, without requiring explicit modeling of all sailing maneuvers. The policy’s input was an observation vector consisting of the distance error to the waypoint, the boat’s heading, the main sail’s heading, and current actuator positions. The outputs directly commanded the tail vane, boat rudder, and front sail actuators, as well as an action for rudder oscillation activation. The full reward function and training formulation are detailed in the Supplementary Materials. The RB controller was used in parallel to provide reference trajectories embedded in the reward. We trained the policy using Proximal Policy Optimization (PPO) (60) in a MuJoCo MJX simulation environment (61), with aerodynamics and hydrodynamics modeled as described in the Supplementary Materials. Although the resulting policy showed strong performance in simulation, its transfer to real-world trials remained preliminary. The RL controller is included as a proof-of-concept to demonstrate that the platform dynamics are compatible with data-driven control approaches, rather than to establish new learning-based control methodologies.

In the trials, the RL controller was run off-board on a laptop connected to the platform via the RFD900ux radio modem. The onboard microcontroller (Teensy 4.1) received the control commands and actuated the servos accordingly. It is possible to run the RL controller onboard by exporting the model in an appropriate format.

Wingsail Airfoil Evaluation

Given that ALBATROSS uses its rigid wingsails for both autorotation during descent and wind-driven propulsion on water, airfoil selection is critical for balanced performance across regimes. The main sail must be symmetrical for bidirectional operation, lightweight for a low center of gravity, and effective at low Reynolds numbers typical of small-scale platforms and variable wind conditions. The operating principle of the main sail is shown in Fig. S4, which involves a windvane mode where no lateral forces are generated, and a sailing mode where the tail vane indirectly controls α_{MS} and lateral lift forces are generated.

Seven rigid wingsail configurations (all rectangular, 220 mm $\times$ 120 mm) were fabricated and evaluated (Fig. 7A): flat-plate polystyrene foam (3 mm thick), Kline-Fogleman modified (KFm) stepped airfoil, cloth sail on carbon frame, NACA0021 balsa with heat-shrink covering, NACA0021 with turbulator strip (2 mm $\times$ 5 mm foam at maximum thickness), a 10% thicker cambered variant of NACA0021, and a Viking square sail-inspired profile. All were pivot-mounted at the quarter-chord (except the Viking sail) with an attached tail vane. A custom fan array (32 micro brushless motors, 600 mm diameter, Fig. 7B) provided repeatable airflow, characterized with a 3D ultrasonic anemometer for uniformity (standard deviation $< 1.0 \text{ m s}^{-1}$ across the test area). Tests approximated low-wind (2 m s^{-1}) and high-wind (4 m s^{-1}) conditions relevant to field operations. Each sail was mounted on a six-axis force-torque sensor and actuated through tail-vane (flap) angles of 0° to 60° in 10° increments. Lift and drag forces were measured in the wind-relative frame to compute lift-to-drag (L/D) ratios.

In low-wind conditions (Fig. 7C), the NACA0021 Turbulator profile achieved the highest L/D ratio (maximum 2.32), outperforming others across most flap angles, followed by the cloth sail and

standard NACA0021. The flat-plate and KFm profiles performed poorly. In high-wind conditions, the thicker cambered NACA variant led with a maximum L/D of 3.1 at small flap angles, with the standard NACA and Turbulator profiles close behind. The flat-plate profile reached only 2.0 (high wind) and 1.1 (low wind). The cloth sail showed good low-wind performance but degraded at small flap angles in higher winds due to flapping. The NACA0021 Turbulator was selected for the main sail of ALBATROSS due to its superior low-wind performance (common in Singapore reservoirs) while retaining competitive high-wind behavior. The standard NACA0021 or thicker variant serve as robust alternatives for higher-wind deployments. These results informed the final sail construction using wire-cut foam with a NACA0021 profile for the L-variant to enhance durability. More details on construction materials and weight of the different sail setups, together with the characterization of the fan array are given in Supplementary Materials.

Biomimetic Rudder Evaluation

To determine an optimal rudder configuration, a series of materials and geometries were evaluated. The rudder profile was designed to be shallow with long chord, resembling a fish tail rather than the typical deep with short chord rudders used in sailboats. A comparative study was conducted using commercially available materials that span a range of stiffness and elasticity. The materials tested, in order of increasing stiffness, include laminated plastic (LP), thin carbon fiber (CF), thick plastic (TP), thick carbon (TC), and thin brass sheets (B) as shown in Fig. 7D.

Lighthill's large-amplitude elongated-body theory (62) was used to model the hydrodynamic forces generated by the biomimetic rudder during oscillation. The rudder prototypes were tested in static oscillation experiments using a water tank setup (see Fig. 7F and movie S6), where each rudder's thrust output and power consumption were measured. They were oscillated to a range of frequencies (0.8 Hz to 4.5 Hz) and PWM amplitudes (55 to 70). The thrust output was measured using an ATI Nano43 force/torque sensor, and the power consumption was recorded using an INA219 current sensor. Based on their thrust-to-power efficiency metric η_α , their best performance was determined. The highest performing material (CF) was then scaled to different lengths (65 mm, 85 mm, 105 mm, 125 mm, and 145 mm) to evaluate the effect of geometry on thrust output and power consumption.

A simulated model, incorporating the hydrodynamic forces generated by the rudder during oscillation based on Lighthill's theory, was created in MATLAB Simulink. The model uses a series of rigid bodies connected by revolute joints to represent the flexible rudder. The spring constant and damping coefficient of these joints were adjusted to match the marker paths of CF-85 rudder (Fig. 7G) to correctly capture the material properties. This simulated model was used to predict the performance of different CF rudder configurations.

The rudder prototypes were also tested in dynamic conditions by integrating them onto the ALBATROSS platform and conducting trials at the swimming pool (Fig. 7E and movie S7). The platform (without sails) was propelled by the rudder (at their best frequency and amplitude settings) to traverse a distance of 4 m, and the speed and power consumption were recorded. The rudder's performance in dynamic conditions was compared against the static water tank results and simulated

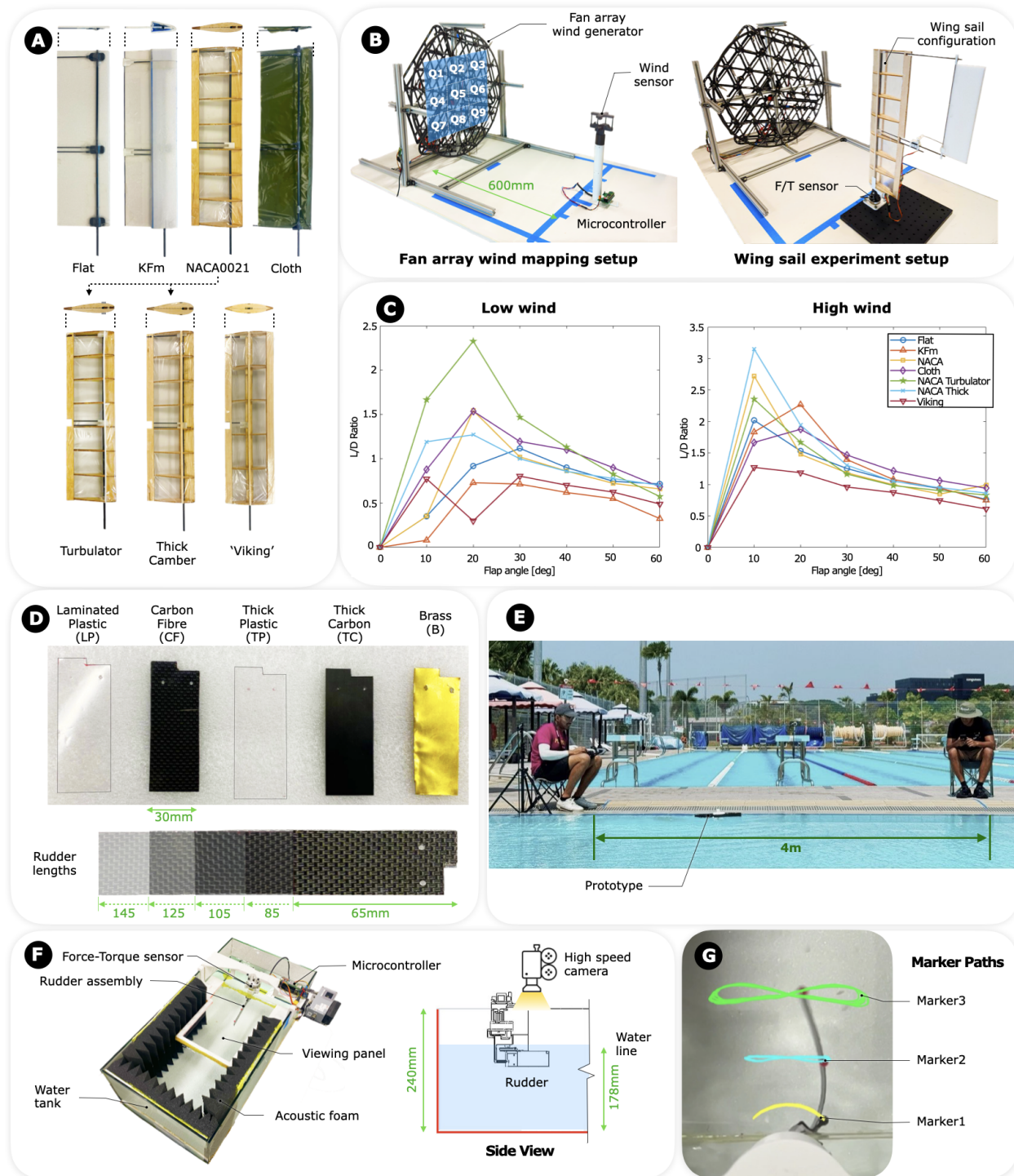


Figure 7: Evaluation of selected airfoils and evaluation of different rudder materials and geometries. (A) The different wingsail configurations tested, where all airfoils are symmetrical, lightweight and easy to prototype. (B) The wind generator test setup and calibration process and wingsail testing using a force-torque sensor. (C) The computed L/D ratios for the different airfoil configurations at low and high wind speeds. (D) The five different rudder materials and the different rudder lengths tested. (E) The experiment setup at the swimming pool to evaluate the dynamic performance of the rudder prototypes. (F) The water tank experiment setup which involves setting up a force-torque sensor and a high speed camera to evaluate the static oscillation of different rudder prototypes. (G) The observed marker paths of CF-85 rudder at optimal setting.

results. A new metric η_β was introduced to evaluate the speed-to-power efficiency of the rudder in dynamic conditions. Although CF-85 achieved the highest speed, as predicted by the simulated model, CF-125 achieved the highest η_β while it ranked third in η_α . This suggests that the longer rudder may be more efficient in dynamic conditions, likely due to its ability to generate more thrust at lower frequencies as it moves in water.

CF-125 was selected as the final rudder configuration for integration onto ALBATROSS due to its highest η_β . A study on sailboat hull lengths and their rudder cross-sectional areas was conducted to ensure the rudder area was appropriate for steering ALBATROSS. The results of the study indicated that a rudder area of approximately 3750 mm² was suitable for a 445 mm hull length, which is consistent with the area of the CF-125 rudder (3750 mm²). More details are provided in the Supplementary Materials.

Supplementary Materials

Supplementary Text

Figs. S1 to S13

Tables S1 to S8

Movies S1 to S9

Data S1

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Author contributions: S.K.H.W. and S.F. proposed the initial idea of the research. S.K.H.W. designed the platform. S.K.H.W., B.L.S. and W.J.A. built the prototypes. S.K.H.W. and B.L.S. conducted experiments for the main sail evaluation and for the biomimetic rudder optimization. L.S.T.W. designed the electronic boards. S.K.H.W., B.L.S., L.S.T.W. and D.S. performed experiments outdoor for aerial deployment and sailing trials. S.K.H.W. and D.S. developed the control algorithms, built simulations and implemented the control system in the prototype. X.C. tested solar charging on the platform and assisted with aerial deployment experiments. S.K.H.W. wrote the manuscript with input from all authors. All authors reviewed the manuscript. S.F. provided funding and supervised the research.

Competing interests: S.K.H.W., L.S.T.W., D.S., and S.F. are inventors on Singapore Patent Application, patent pending, titled “ALBATROSS: A bio-inspired, aerially deployable, autonomous sailing sensor platform,” through Singapore University of Technology and Design (Patent Application Number 10202602936U).

Data, code, and materials availability: All data needed to evaluate the conclusions in the paper are present in the main text or the Supplementary Materials and are available at Zenodo (DOI: 10.5281/zenodo.21485808). All materials were commercially available.