ARSEM

Autonomous Robotic Sailboat for Environmental Monitoring

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Abstract

Global ocean observation remains limited by the high cost, energy demands, and restricted accessibility of existing data-collection systems such as research vessels, moored buoys, autonomous underwater gliders, and satellite-based sensors. While each of these technologies contributes valuable information, none provide a scalable, long-endurance, and navigationally flexible platform capable of collecting high-resolution *in situ* environmental data across remote ocean regions. To address this gap, we propose ARSEM—an Autonomous Robotic Sailboat for Environmental Monitoring designed to operate for extended durations without human intervention or external fuel. ARSEM relies on wind propulsion and solar energy to power control electronics, navigation systems, and environmental sensors, enabling ultra-low-power, long-range missions.

The expected outcome of this work is a fully autonomous, energy-efficient surface vehicle capable of collecting high-quality environmental data in under-sampled oceanic regions at a fraction of traditional operational cost. ARSEM aims to serve as a scalable research platform for oceanography, climate science, and long-term environmental monitoring, with open-source components designed to support future research and interdisciplinary collaboration.

1 Introduction and Background

Despite the major advancements in technologies such as satellite, underwater robotics and remote sensing, our understanding of the planets oceans are surprisingly limited. Modern satellite measurements reliant on altimetry and gravity measurements allow us to approximate large-scale seafloor structures, but these methods lack the resolution required for scientific, ecological or climatological analysis.

While satellite missions are capable of picking up surface-accessible data such as Sea Surface Temperature, Sea Surface Height, Surface Chlorophyll, Ocean Colour, Surface Wind Speeds, etc. they do so at resolutions poor compared to that of *in situ* methods. In addition, satellites are unable to pick up data such as Dissolved Oxygen, Oceanic pH, Nutrient Concentration, Microbial Activity, and other characteristics that require measurement beyond the superficial layers of the oceanic surface.

In contrast to satellite observations, *in situ* ocean data is typically collected either using free-floating platforms, fixed buoys, underwater gliders, or research vessels. While these methods are capable of collecting data from far below the ocean surface at high resolution, they come with their own set of limitations. Ship based expeditions are very expensive, logistically complex and geographically constrained. This results in episodic coverage resulting in poor long term coverage, especially in harsh and remote environments. The installation of platforms and buoys too require expensive oceanic deployment missions; in addition, free floating platforms are subject to being captured by ocean currents and thus face geographic limitations. On the other hand moored buoys have no movement whatsoever.

Many commercial ships that are part of programs such as the Voluntary Observing Ships (VOS) coordinated by the World Meteorological Organization, and the Ship of Opportunity Program (SOOP) also collect data on daily voyages. However, most copmmerical vessels limit their journeys to trade routes, thus leaving remote parts of the ocean unexplored.

Given these constraints, there remains a clear need for an ocean-observing platform that combines the high-resolution of *in situ* methods that are low maintenance (such as platforms and buoys) while preserving the wide spread area coverage that research vessels have. This motivates the development of ARSEM – the Autonomous Robotic Sailboat for Environmental Monitoring. By relying on wind propulsion for locomotion and solar energy to power on board electronics, ARSEM is designed to operate for extended durations without human intervention or external fuel, allowing it to explore remote areas of the planets oceans for a fraction of the cost that it does currently. ARSEM may actively navigate to areas of scientific interest, while carrying scientific payloads to measure ecological, biochemical, and climatological parameters that satellites otherwise cannot pick up. ARSEM thus provides a low-cost, energy efficient, autonomous and highly navigable platform capable of gather high resolution *in situ* environmental data across remote and under-sampled ocean regions, thereby addressing the existing observational gaps that currently employed methods fail to overcome.

2 Prior Art

Autonomous Surface Vehicles (ASVs) for collecting oceanic data do currently exist, and while they address certain components of the data-gap described previously, none of these systems provide a complete or cost-effective solution for widespread environmental monitoring. Existing ASVs typically face constraints in affordability, navigational flexibility, sensor modularity, and accessibility to academic or developing-world researchers. The following subsection outlines the most prominent systems in use today, along with their respective limitations.

2.1 Saildrone

Saildrone vehicles are among the most advanced ASVs currently deployed for long-range oceanographic missions. These platforms use a rigid wing-sail for propulsion and rely on solar energy to power onboard electronics, enabling multi-month missions across remote oceanic regions. Saildrones are capable of collecting a variety of surface and near-surface measurements including meteorological variables, sea surface temperature, ocean–atmosphere CO_2 fluxes, acoustic backscatter, and limited biological proxies.

Despite their strong capabilities, Saildrone systems remain prohibitively expensive for most institutions, with high capital and operational costs limiting their accessibility. Their sensor payloads and software stack are proprietary, resulting in limited customizability for specialized scientific missions. In addition, logistical constraints on deployment and recovery require coordination with research vessels or support infrastructure, which increases overall mission cost. As such, although Saildrones address certain challenges of autonomous in situ data collection, they do not provide a scalable or low-cost solution for widespread ocean monitoring.

2.2 Wave Gliders

Wave Gliders, developed by Liquid Robotics, utilize wave energy for forward propulsion while relying on solar panels to power onboard sensors. This dual-energy approach enables long-duration deployments and makes Wave Gliders particularly effective for monitoring surface conditions and conducting acoustic surveys. Their ability to operate continuously without fuel is a significant advantage in remote regions.

However, Wave Gliders suffer from limited navigation authority due to their slow speeds and reliance on wave-driven propulsion. Strong ocean currents, storms, or unfavorable sea states can significantly impair their navigational accuracy. In addition, like Saildrones, Wave Gliders are expensive platforms, placing them out of reach for many universities and research groups. Their payload capacity is also constrained, limiting the variety of biogeochemical instruments that can be carried on a single mission.

2.3 Underwater Gliders

Underwater gliders such as the Slocum, Seaglider, and Spray Glider operate by adjusting buoyancy to glide through the water column, allowing them to collect subsurface measurements of temperature, salinity, and certain biogeochemical parameters. Gliders represent a major advancement in long-range autonomous oceanography and have significantly improved our understanding of subsurface stratification and circulation.

Nevertheless, underwater gliders are not suited for continuous surface measurements, which are crucial for studying air–sea interactions, meteorology, and carbon exchange. They are also unable to maintain precise horizontal trajectories in strong currents and require ship-based deployment and recovery. Furthermore, their sensor payloads are limited by power and buoyancy constraints, making them unsuitable for carrying heavier or more complex instrumentation.

2.4 Argo and Biogeochemical Argo Floats

The global Argo program constitutes the backbone of autonomous ocean observation, with thousands of profiling floats measuring temperature and salinity throughout the upper 2000 m of the ocean. A subset of the array, known as Biogeochemical Argo, includes additional sensors for oxygen, nitrate, pH, and optical properties. These floats provide invaluable high-resolution vertical profiles on a global scale.

However, Argo floats drift passively with ocean currents and cannot navigate toward specific regions of interest. Their profiling cycle, typically once every 10 days, results in coarse temporal resolution, and their sensor suite remains limited compared to what can be carried on larger platforms. Coverage is particularly sparse in remote and high-latitude regions where data is critically needed. As such, Argo floats complement but cannot replace mobile, surface-operating autonomous platforms.

2.5 Drifting and Moored Buoys

Drifting buoys and moored buoy arrays, such as those used in the TAO/TRITON, PIRATA, and RAMA networks, provide long-term measurements of surface temperature, winds, and air–sea fluxes. These systems offer high-quality time series data that are essential for climate and weather prediction.

Their major drawback, however, lies in their lack of mobility. Drifting buoys are carried by ocean currents and cannot be directed toward specific scientific targets, while moored buoys are fixed to a single location. Both require expensive deployment missions, and moored systems are vulnerable to biofouling, damage, and vandalism. Consequently, although these instruments are scientifically valuable, they do not offer broad spatial coverage or adaptive sampling capabilities.

Summary of Limitations

Existing autonomous technologies each address particular aspects of ocean monitoring, but none achieve the combination of low cost, long endurance, navigational autonomy, and modular scientific instrumentation required for comprehensive environmental monitoring across remote ocean regions. This technological gap motivates the development of ARSEM as a novel platform designed to integrate the strengths of existing systems while overcoming their limitations.

3 Objectives

The ARSEM project has the following objectives.

- To have a physically and aerodynamically sound sailboat capable of surviving harsh oceanic conditions without damage or capsizing.
- Design and program a controller circuit to manipulate the control surfaces (the sail and the rudder) of the boat.
- Program an versatile onboard computer capable of navigating the boat only using GPS + magnetometer localization along with onboard monitoring instruments (such as an anemometer).
- Design and implement redundant multimodal communication systems to and from the robot. The systems under consideration have been listed below.
  - RC Control
  - Long Range (LoRa) serial communication
  - Satellite Communication

- Integrate a fully operational battery management system (along with solar cells and Lithium ion batteries) to power the robot. The BMS must be capable of supporting low-power modes.
- Develop fault detection and redundancy protocols.
- Implement onboard data logging and transmission pipelines for storing, compressing, and relaying scientific data efficiently under bandwidth-limited conditions.
- Install environmental monitoring sensors such as

4 Expected Deliverables

- This project is expected to produce a fully functional, aerodynamically sound and structurally strong sailboat capable of surviving and navigating water bodies of water completely autonomously. The robot is expected to relay observational data collected *in situ* back to a "home base" server via satellite communication.
- A deterministic algorithm capable of navigating the robot will be completed, configured and setup on the primary computer. One must entertain the possibility of a peripheral slightly more computationally heavy Reinforcement Learning Model as an alternative.
- A peripheral project of building a complex simulation to test the algorithms against simulated environments will be developed.
- Quantitative evaluation of ARSEM's navigation accuracy, energy efficiency, and communication reliability under simulated and field-tested conditions.
- A curated dataset of collected environmental parameters, which may be used for validating climate, oceanographic, or control system models.
- Certain design files, algorithms and datasets will be made open-source to encourage future research.

5 Methodology

This section outlines the methodology to be employed to facilitate the design, development and testing of ARSEM.

5.1 Physical Design

After considering multiple initial designs, it was decided to base the design of the hull sailboat on a "Racing Shell", an extremely narrow lightweight rowing boat. The design was chosen for it's point symmetry – preserving performance both going forward and backward; and for its speed.

The hull is to be fabricated by 3D printing the initial shape and using it to create a sanded down and polished fiber glass hull. The material fiber glass was chosen for its ease of use, strength and smoothness.

The keel and its bulb – two key components of the boat in terms of aerodynamics and stability are to be made out of steel sheets and melted lead respectively. The steel sheets used for the keel are to be smoothened into airfoil-like shapes to prevent drag. The lead bulb must be made heavy to move the center of mass of the boat lower, preventing it from capsizing.

The rudder of the boat, unlike in conventional designs of the sailboat, will be placed in the air instead of the water, allowing the boat to use the atmosphere for stable orientation instead of the hydrosphere. This design, suggested by Professor Ruina, is to improve the orientational stability of the vessel.

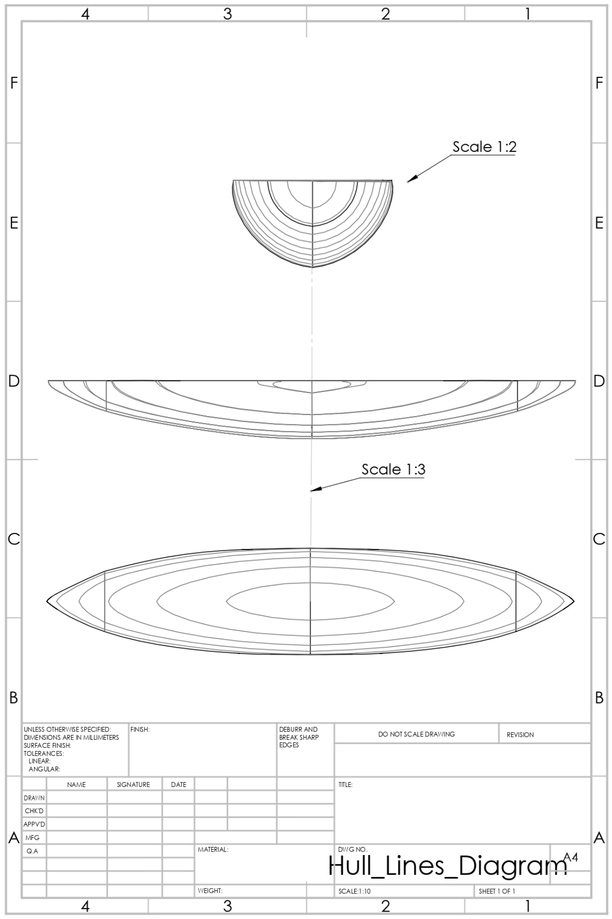

Figure 1: Hull Design

5.2 Electronics

5.2.1 Controller – Servo Control

The control surfaces (the sail and the rudder) are mounted on a custom built coaxial motor shaft. The geared motors used are operated as servo motors with the help of a microcontroller (Raspberry Pi Pico). The microcontroller is fed instructions from the primary computer of the robot, and carries out servo motor functionality with the help of magnetic hall-effect motor encoders and redundant mechanical encoders used for calibration.

5.2.2 Communications

A robust and redundant communication subsystem is essential for ensuring reliable interaction with ARSEM during both testing phases and long-duration autonomous missions. The communications architecture is designed as a multi-modal system combining Long Range Radio (LoRa), Automatic Identification System (AIS), Satellite Communication (SatCom), and short-range Radio Control (RC). This layered approach ensures that ARSEM remains reachable under diverse operating conditions, from controlled inland testing environments to remote open-ocean deployments. At present, LoRa communication forms the core of the implemented system, while the remaining modalities constitute planned future extensions of the communications pipeline.

The protocol for Long Range (0–10 km) communication has been developed using the REYAX© RYLR998 LoRa module. The module offers configurable bandwidth, spreading factors, and forward error correction (FEC) parameters. These capabilities enable reliable low-bandwidth telemetry exchange even in high-interference or obstructed environments. Additionally, the module provides transparent UART-based ASCII transmission, simplifying integration with both microcontrollers and the onboard embedded Linux system.

The current control paradigm enables two-way communication between the base station and the sailboat. The base station can request remote sensing parameters such as wind speed, sail and rudder angles, GPS coordinates, IMU readings, and the health status of onboard subsystems. The sailboat receives and processes these commands, and transmits METAR-style weather summaries, diagnostic data, and sensor updates in return. Because the LoRa modules only support ASCII payloads, a custom communication library has been developed to encode telemetry frames using BASE64. This approach ensures safe transport of binary sensor values, avoids delimiter conflicts, and provides consistent decoding on both ends.

While LoRa forms the currently operational communication layer, the long-term communications strategy will expand significantly. Future iterations of the pipeline will incorporate error checking for improved reliability and packet sequencing with acknowledgments to detect and recover from dropped frames. The communication stack will eventually integrate SatCom for global connectivity during oceanic missions, enabling ARSEM to transmit data and receive instructions even far from shore. AIS functionality will also be introduced to broadcast surface position to nearby vessels for safety, and RC control will serve as a rapid-response manual override during field testing or early deployment trials. Over-the-air configuration updates and dynamic adjustment of LoRa parameters are also planned to ensure adaptability under variable environmental and radio conditions.

At the hardware level, the communications subsystem is organized around the master Raspberry Pi onboard the sailboat. The Pi interfaces with the REYAX LoRa module over UART, the RC receiver through PWM/PPM channels, and—when integrated—the SatCom modem over USB-UART. Planned failover logic will allow the system to automatically switch communication modes based on link availability, ensuring continuous contact with the platform throughout its mission lifecycle.

Workflow for Communication Pipeline

Communication Workflow
1. Base Station generates command or telemetry request
2. Message encoded using BASE64 + CRC-16 checksum
3. Message transmitted via LoRa / SatCom / RC layer (as available)
4. Sailboat receives message via Raspberry Pi UART interface
5. Message decoded, verified, and forwarded to microcontroller
6. Control surfaces or sensors respond to command locally
7. Sensor data and system status packaged into structured frames
8. Data returned to base station via highest-available communication link

Required Tools, Software, and Resources

- REYAX RYLR998 LoRa modules (base and sailboat)
- Raspberry Pi (Sailboat master computer)
- RC transmitter and receiver system
- Satellite communication module
- Python libraries for serial communication (pyserial)
- Custom C/Python BASE64 encoding/decoding libraries

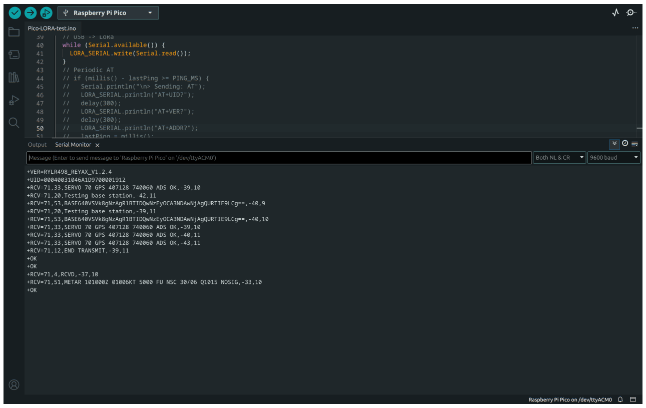

Figure 2: Base station interface displaying outgoing commands and telemetry requests during early LoRa protocol testing.

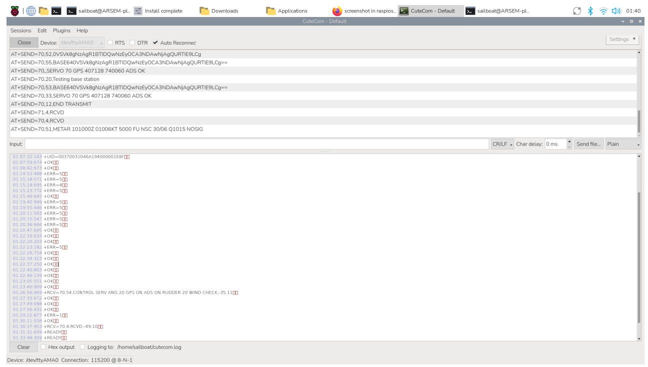

Figure 3: Sailboat Raspberry Pi terminal receiving/sending data as AT commands to the LoRA module

Figure 4: Bidirectional LoRa communication between the base station and ARSEM during preliminary testing.

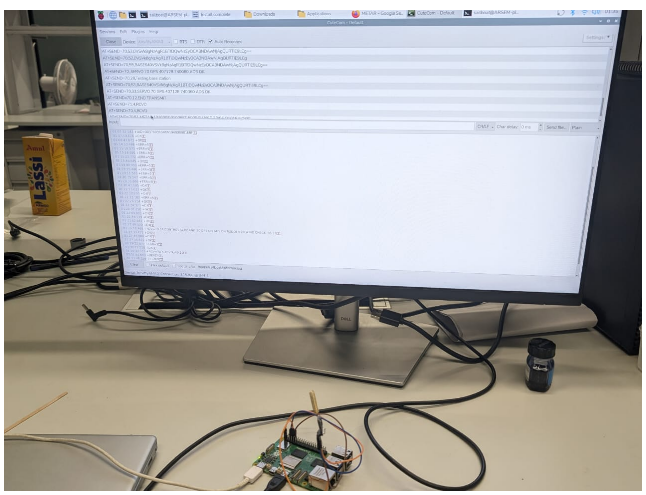

Figure 5: Sailboat-side communications hardware undergoing commuications testing

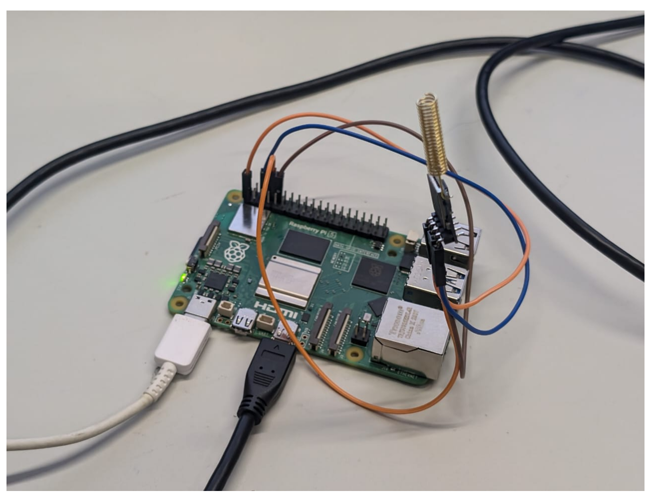

Figure 6: LoRA + Master Computer (Raspberry Pi 5)

Figure 7: Field-testing setup demonstrating integration of multiple communication modalities on ARSEM.

5.3 Navigation Algorithm

The navigation of the sailboat is broken down into two primary components – a global path planning that optimizes a route based on wind speeds, wind and water currents and land masses. This is exemplified in figure 8.

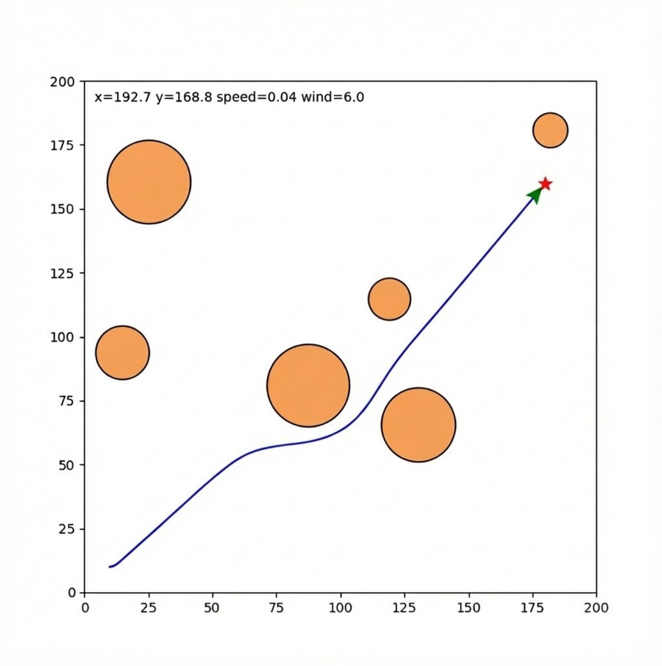

Figure 8: Global Path Planning

The local path planning will take into account the immediate environmental winds to ensure that the boat adheres to the global plan to the best of its ability. This can be done in either of two ways using traditional programming.

1. Using experimental data, one can generate boat polar. The resultant boat polar may be fed into either a greedy algorithm or a dynamic program.
2. Build a highly mathematical physics-based deterministic algorithm.

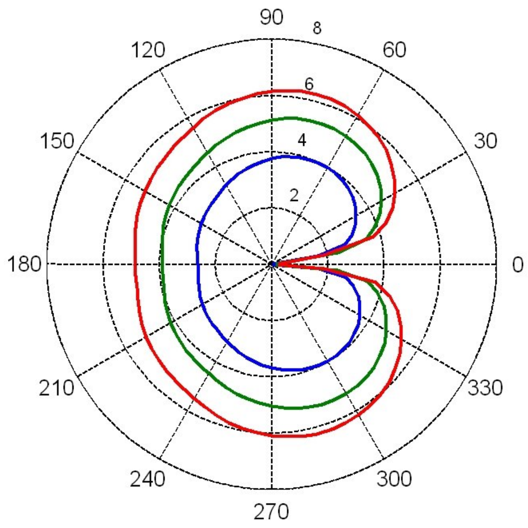

Figure 9: Boat Polar. Credit: Ryad Benosman

6 Semester-Wise Plan

Semester	Key Activities and Steps	Expected Outputs
Semester 4	• Complete fabrication of the first physical designs. • Setup redundant communication protocols. • Fully functional manual control over the boat. • Manual global planning, greedy local planning algorithms. • Implement basic fault detection and error handling system.	• First working prototype of ARSEM – testing in large water bodies. •
Semester 5	• Integrate readily available meteorological data into global path planning. • Start building basic simulation based test beds. • Advanced fault detection and error handling protocols.	• Fully autonomous trips. • Physics-engine based novel simulations. • Added versatility.
Semester 6	• Integration of environmental sensing devices. • Completely autonomous global and local path planning.	• Longer unsupervised large water body missions. • Build database of various *in situ* oceanic environmental data.

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