# Littoral Magnetic and Water Column Survey Underwater Glider*

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***Abstract*— Water column survey is currently expensive due to the cost of platforms and operation. A new, low-cost sampling tool is required that can effectively measure the water column over a large area. This paper presents an underwater glider for littoral magnetic and water column survey. The focus is to bring Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) from the proof-of-concept short range stage to long endurance operational readiness. The ROUGHIE has been designed and prototyped by the Nonlinear and Autonomous Systems Lab over the past 6 years and is already the most maneuverable internally actuated underwater glider due to its unique roll design. The ROUGHIE is capable of performing 3 meter radius turns in shallow water. With updates to robustness and ease of use, the platform will be a capable exploratory tool to aid marine research. The proposed design update includes upgrading the buoyancy system to a piezoelectric pump and updating the controller to a frontseat-backseat controller with a web based interface. The significant payload capability of the ROUGHIE will be used to haul a CTD, flourometer & turbidity sensor, and high quality magnetometer. With these sensors, the ROUGHIE will be able to accurately map dense oceanographic features.**

***Index Terms*— Marine Robotics; System Design; Underwater Glider; Autonomous Underwater Vehicle**

## I. Introduction

Water column studies have traditionally been restricted to large scale surface vessels with towfish, expensive autonomous underwater vehicles (AUVs), and drifting buoys such as Argo [1]. A low-cost AUV that is able to explore the upper 100 meters of water column and carry important sensors for extended missions is critical for improving our understanding of the ocean. Important sensors for a water column sampling missions include a conductivity, temperature, depth probe (CTD), turbidity sensor, and flourometer. Additionally, carrying a high-fidelity magnetometer has recently become feasible with AUVs to help study magnetic anomalies in the ocean caused by metal objects such as seamines or geophysical structures such as the effect of seafloor spreading.

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Fig. 1: The current revision of ROUGHIE during pool testing

One category of AUV naturally lends itself towards water column exploration and magnetic surveys, the underwater glider. Gliders are buoyancy propelled vehicles that travel through the water in a sawtooth pattern and maneuver through internal mass shifting [2]. This style of flight is extremely efficient leading to extended mission endurance [3]. In addition, underwater gliders are nearly acoustically and electrically silent during operation with a low-power state occurring during the majority of flight time. This results in a limited environmental impact and increased probability of evading detection from outside observers.

Considering the natural advantages of underwater gliders for water column survey missions, an ideal platform for this mission is a highly maneuverable, low-cost underwater glider. This paper presents the design overhaul required to bring the Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) [4]–[6] from the proof-of-concept stage to operational readiness, Fig. 1. The ROUGHIE is already the most maneuverable internally actuated underwater glider [7], however it has a significant magnetic signature and is not currently designed to accommodate the extensive sensor suite required for water column surveys. Further, the ROUGHIE as a proof-of-concept vehicle requires significant training to operate or modify safely. Improvements to the overall control strategy, user interface, and shipboard setup are required to make the platform more accessible for general users. The platform also needs a design update to improve overall robustness for long duration, real-world operation. This design update builds upon the existing modular design infrastructure that separates functionality into a ballast module, pitch module, roll module, and control module. The four modules enable the ROUGHIE to control depth, pitch, and roll in order to navigate through the water along a sawtooth path. The ballast module is sometimes referred to as the buoyancy module.

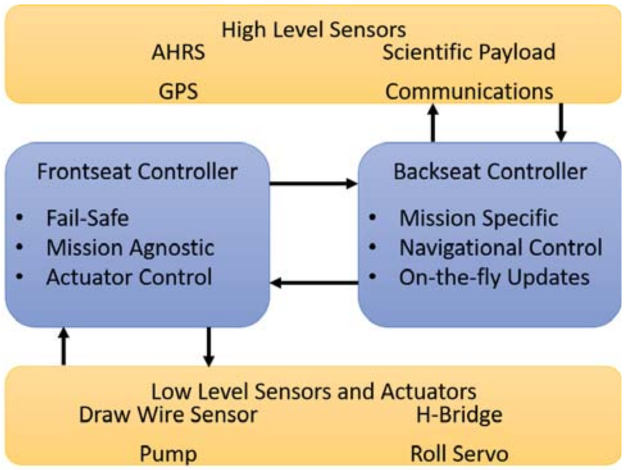


Fig. 2: The ROUGHIE controller will follow a frontseat-backseat approach with high-level control being handled by the backseat controller and low-level control handled by the frontseat controller.

The remainder of this paper presents the upgrade concept in Sec. II, the design solution in Sec. III, vehicle synthesis in Sec. IV, schematics in Sec. V, cost estimates in Sec. VI, development schedule in Sec. VII, and concludes with Sec. VIII.

## II. Concept

The ROUGHIE is a small, low-cost underwater glider [6]. Fundamental to the ROUGHIE functionality is the rail based design. In this design concept, nearly all the internal components are mounted on top of a single rail. The rail is then suspended inside of the hull with a roll module. The roll module is able to effectively actuate nearly all of the internal mass of the vehicle causing dramatic roll moments. With this design idea, the ROUGHIE is already capable of performing the tightest internally actuated turns with a radius down to 3 meters [7].

As the ROUGHIE has historically been used exclusively for controls validation it is not currently capable of performing long duration water quality measurements. To upgrade the ROUGHIE for water column sampling, it requires a full overhaul of major systems to improve robustness and increase user friendliness. Once the overhaul is complete, the ROUGHIE will be capable of operating for moderate to long endurance water column sampling missions that are currently not feasible without costly equipment and manned support craft.

To make the vehicle accessible for the greater underwater community the user interface must be significantly refined. Wireless command and control will be enabled through a wifi link allowing high speed communication. This command and control infrastructure will be implemented in a web interface so that any device with wifi can control the vehicle. The user interface will be refined to allow control of mission parameters such as waypoints, survey area, sensor payload, and fail-safe control. Long range communicaton will be completed using Iridium Short Burst Data. The overall control strategy will follow a frontseat-backseat approach similar to some other marine platforms [8], Fig. 2.

As a small platform (15kg), the ROUGHIE is easy to deploy and can be launched by hand. The current iteration of the ROUGHIE is able to operate in shallow water with a minimum depth of 3 meters enabling launch from shore reducing the cost of deployment.

## III. Design Solution

Design of a low-cost water column sampling tool involves many tradeoffs as the design is optimized. The most notable decision with the ROUGHIE is to not include any kind of thruster and instead use buoyancy as the propulsion method. As an underwater glider, it is slow but can operate with an extended endurance over traditional propeller driven vehicles. Further, the traditional ‘sawtooth’ pattern followed by underwater gliders means that the ROUGHIE will be able to sample the entire water column without additional energy expenditure. For traditional propeller based vehicles to sample the full water column the vehicle must expend significant energy to travel in the vertical plane.

In order to make the ROUGHIE accessible for water column missions, the vehicle must be able to explore complex water features such as ocean fronts. To accomplish this, the ROUGHIE must be able to perform maneuvers and turns with a very tight radius. To achieve a tight turning radius, the ROUGHIE design mounts the majority of internal components on a rail. The rail is then actuated with a roll module. This design choice results in the vehicle being highly maneuverable, however it does impact the free space available inside of the hull and introduces some technical challenges due to the moving nature of the internal components. With the roll module, the ROUGHIE has been able to achieve the tightest turns of any internally actuated underwater glider [6].

In order to measure magnetic anomalies in the water, the vehicle must not exhibit a significant magnetic signature. This is accomplished through designing with non-magnetic components when possible and minimally magnetic components when necessary. The component from the original ROUGHIE with the strongest magnetic signature was the pump. To resolve this, a non-magnetic piezoelectric solid-state pump from Kinetic Ceramics will be used. This pump contains no magnetic components and has equivalent performance to magnetic pumps.

Optimization for battery capacity and endurance was completed based on the major components and assuming negligible other losses. Hotel load on the AUV includes the Raspberry Pi Zero and Arduino. These two platforms combine to roughly 0.5W continuously. When operating in steady state, this is the only draw on the system (excluding sensor load). During the inflection point between glides the AUV must control bouyancy, pitch, and roll. Based on experience with the existing ROUGHIE, pumping to control buoyancy is the most significant power draw at up to 100W. Pumping events take roughly 8 seconds to complete and

TABLE I: Estimated performance

| Metric | Performance |
|---|---|
| Diameter | 13cm |
| Length | 1.3m |
| Mass | 15kg |
| Depth | 200m |
| Turn Radius | 3 m |
| Endurance | 3 days |
| Connectivity | wifi/Iridium SBD |
| Interface | web |
| Integrated Sensors | CTD, Turbidity, Flourometer, Magnetometer |
| Additional Payload | 3 kg |

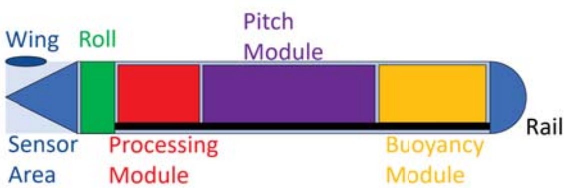


Fig. 3: Schematic of the vehicle. The modular design approach includes the buoyancy module, pitch module, processing module, and roll module. Outside of the vehicle is the flooded rear end cap for wet sensors near the wing.

only occur at inflection points. During pool testing with the current ROUGHIE, the average vertical speed has been 0.1 meter per second. This will result in 1000 seconds between pumping events for 100 meter glides for an average pump power consumption of 0.8W. Feedback control and sensor loads are harder to quantify, but should remain less than an average of 0.7W bringing the total average consumption to 2W. Assuming a target operation time of three days, the total battery capacity needs to be at least 144Wh, with higher capacities being preferred to enable long term operation in shallower water and to accommodate unplanned loads such as sensors. The existing ROUGHIE uses a 326Wh battery pack which will be maintained for the new iteration of the platform.

## IV. Synthesis

The major upgrades described in Sec. II and III will impact the performance and operation of the ROUGHIE. Following the upgrade, the vehicle is expected to attain the performance outlined in Table I at a cost per vehicle of $12,900 USD (excluding sensors). Key attributes of the proposed non-magnetic ROUGHIE include a depth rating of 200m, a minimum endurance of 3 days, wifi and Iridium SBD connectivity, a large integrated sensor suite, and the possibility to integrate more sensors in the flexible 3kg payload. Further, the vehicle maintains its 3m turn radius [7] enabling it to perform tight spiral maneuvers for true water column sampling as well as more complex maneuvers such as s-turns and figure-8s.

## V. Schematics

In this concept design for a low-cost water sampling underwater glider, several changes are made to the ROUGHIE. Overall, the layout has not changed significantly from earlier revisions [6]. Specific updates include extending the ballast module to accommodate the new piezoelectric pump and additional space for wet sensors in the rear of the vehicle. The vehicle physical layout is shown in Fig. 3. Electrical layout is shown in Fig. 4. The vehicle hull is made out of a custom manufactured carbon fiber tube sealed with double piston o-rings in aluminum end caps. Inside of the sealed pressure vessel are all the major components suspended on a mounting rail. The front of the rail is occupied by the ballast module. This module contains a fixed ballast tank and the piezoelectric pump. It's forward location relative to the center of buoyancy causes the vehicle to naturally pitch up when gliding upwards and pitch down when gliding downwards, thus reducing the amount of motion required from the sliding pitch mass. Behind the ballast module is the pitch module. The pitch module contains a 25.9V 12.6Ah lithium ion battery pack. The battery pack is mounted on a linear actuator to slide the pack forward and aft in the vehicle to control pitch. At the rear of the rail is the processing module. This module will require a significant overhaul to accommodate the required new control features. The processing module will be upgraded to a frontseat-backseat architecture similar to some other underwater vehicles [8]. Additionally, the processing module contains the power and communication systems onboard the ROUGHIE. At the rear of the pressure vessel is the roll module. This module changes the orientation of all the internal components relative to the hull causing a large rolling moment. This roll moment in turn results in the hull (and wing) to roll until the center of gravity and center of buoyancy are vertically aligned. Through the use of the roll module, the ROUGHIE can achieve dramatic roll angles only constrained by servo choice. Outside of the pressure vessel on the rear of the vehicle is a wet sensor area and the rear mounted wing.

## VI. Cost

To reduce the overall cost of the vehicle, low-cost components that take advantage of emerging technologies were chosen. These components, when coupled with the rail-based, modular design enable the ROUGHIE to perform as described in Sec. IV. The estimated cost per vehicle is described in Table II. Major components are the scientific payload, the inertial navigation suite, and the non-magnetic pump. The scientific payload includes a CTD, a flourometer & turbidity sensor, and a magnetic sensor. The CTD is a Star-Oddi DST CTD online. This small CTD provides a small and easy to integrate package. The flourometer & turbidity sensor is a WET Labs ECO Puck combo flourometer-turbidity sensor measuring chlorophyll-a in $\mu g/L$ and turbidity in $NTU$. The magnetic sensor is a Twinleaf microSAM. The microSAM is an extremely light weight sensor with magnetic sensitivity of $20pT/Hz^{1/2}$. For navigation, a Sparton AHRS-M2 provides high fidelity dead-reckoning underwater. While surfaced, a GPS provides localization. Locomotive force is provided by a Kinetic Ceramics pump. As a piezoelectric pump, the system has no permanent magnetic signature

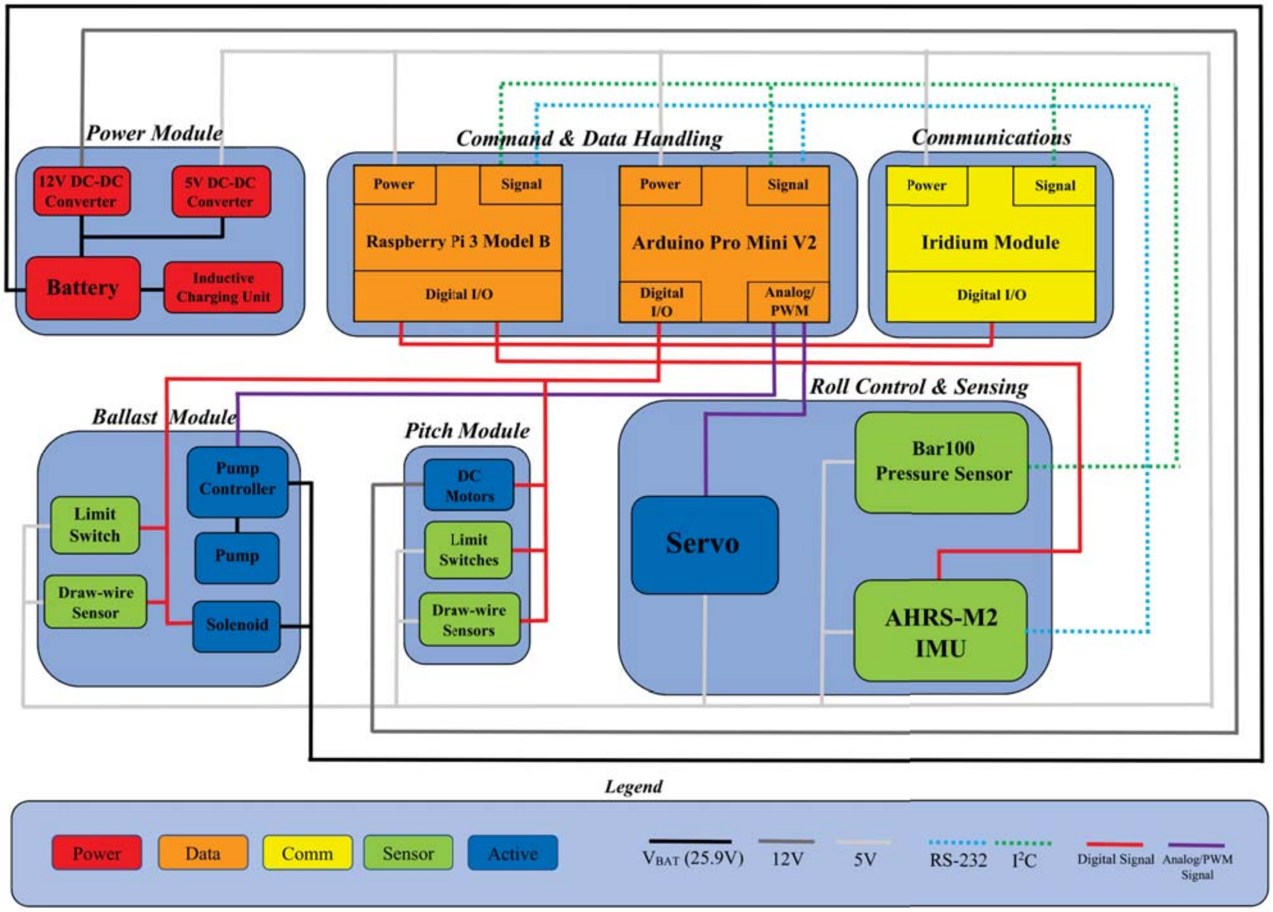


Fig. 4: Electrical schematic showing connections between the different modules and components in the ROUGHIE.

TABLE II: Estimated costs of the non-magnetic ROUGHIE

| Item | Cost (USD) |
|---|---|
| Raspberry Pi | 35 |
| Arduino Pro Mini | 10 |
| Iridium SBD | 250 |
| Custom Electronics | 220 |
| Inertial Navigation | 1850 |
| Battery | 335 |
| Pitch Motors | 40 |
| Draw Wire Sensors | 370 |
| Roll Servo | 180 |
| Piezoelectric Pump | 6500 |
| 3D Printed Components | 1000 |
| Machined Components | 1000 |
| Hull | 700 |
| Misc. Hardware | 500 |
| CTD | 3500 |
| ECO Puck Combo | 12000 |
| Magnetic Sensor | 9000 |
| Total (excluding sensors) | 12990 |
| Total (including sensors) | 37490 |

meaning that it will not impact scientific measurements. Iridium Short Burst Data (SBD) is used for mission status updates while in open water using a RockBlock 9603.

## VII. Schedule

The design (Fig. 3) enables each module to be designed with minimal interactions between modules resulting in an accelerated design process. Additionally, this upgrade process will be accelerated due to the authors experience working with and developing on the original ROUGHIE [6], [7] and Bluefin SandShark [8], [9]. Taking this abbreviated development schedule into account, the timeline for development is in Table III. In the schedule, initial design involves electromechanical updates which enable the new mission. Following manufacturing, a fully assembled glider will be ready for controls development. The glider will employ a frontseat-backseat control architecture, Fig 2. The frontseat controller encompasses the low-level controllers which actuate components, perform deterministic feedback control; it also serves as a watchdog. The backseat controller determines mission goals, optimal trajectories, and executes the dead reckoning algorithms. Development of the backseat controller will take significantly longer than the frontseat. Once the vehicle is functional with a frontseat-backseat control architecture, the user interface will be developed. This user interface will be web based, supporting mobile browsers, and enable the user to choose different mission waypoints and behaviors by clicking on a map and configuring the target mission. Mission parameters will be wirelessly transferred to the vehicle over Wifi when in range, and Iridium SBD when in open water. The scientific payload will then be fully integrated into both the backseat controller and

TABLE III: Estimated development timeline

| Item | Duration (weeks) | Start | End |
|---|---|---|---|
| Initial design | 6 | 0 | 6 |
| Manufacturing of glider | 5 | 6 | 11 |
| Development of frontseat controller | 3 | 11 | 14 |
| Development of backseat controller | 10 | 14 | 24 |
| Development of user-interface | 6 | 24 | 30 |
| Sensor integration | 8 | 30 | 38 |
| Open water validation | 10 | 38 | 48 |

the user interface prior to open water validation, approximately 1 year after start of the project.

## VIII. Conclusion

This paper presented a roadmap to design a litttoral magnetic and water column survey underwater glider. This roadmap is based on an overhaul of the ROUGHIE platform to increase its functionality as a data collection tool. Major upgrades include changing the pump to a non-magnetic piezoelectric pump and updating the control system to be a frontseat-backseat configuration. The vehicle has been specified to carry a flourometer & turbidity sensor, CTD, and magnetometer. With this sensor payload, the ROUGHIE can be used to simultaneously survey the water column and build magnetic maps. Control of the platform is achieved through a high-level web based interface that can be accessed on any device with wifi including mobile phones. Through this web interface, the mission parameters such as trajectory and sensor specifications can be set. The updated ROUGHIE is low-cost and easy to deploy at $\$12,990$ USD excluding sensors and 15kg. This means that the ROUGHIE can be beach launched or launched from a ship with a minimum estimated endurance of 3 days.

The development process is underway with expected open water validation of the design updates in the next year. Following initial validation, the control system will be validated including fail-safe behavior, navigation, and online mission planning.


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## References


[1] R. E. Davis, "Observing the general circulation with floats," *Deep Sea Research Part A. Oceanographic Research Papers*, vol. 38, pp. S531 – S571, 1991. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0198014912800239

[2] J. Sherman, R. Davis, W. Owens, and J. Valdes, "The autonomous underwater glider "spray"," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 437–446, Oct 2001.

[3] C. D. Haldeman, O. Schofield, D. C. Webb, T. I. Valdez, and J. A. Jones, "Implementation of energy harvesting system for powering thermal gliders for long duration ocean research," in *OCEANS 2015 - MTS/IEEE Washington*, Oct 2015, pp. 1–5.

[4] B. R. Page, S. Ziaeefard, P. Morath, V. Stumbris, and N. Mahmoudian, "Roughie 2.0: Improving performance using a modular design approach," in *OCEANS 2017 - Anchorage*, Sept 2017, pp. 1–5.

[5] S. Ziaeefard, B. R. Page, A. J. Pinar, and N. Mahmoudian, "A novel roll mechanism to increase maneuverability of autonomous underwater vehicles in shallow water," in *OCEANS 2016 MTS/IEEE Monterey*, Sept 2016, pp. 1–5.

[6] B. R. Page, S. Ziaeefard, A. J. Pinar, and N. Mahmoudian, "Highly maneuverable low-cost underwater glider: Design and development," *IEEE Robotics and Automation Letters*, vol. 2, no. 1, pp. 344–349, Jan 2017. [Online]. Available: https://doi.org/10.1109/LRA.2016.2617206

[7] S. Ziaeefard, B. R. Page, A. J. Pinar, and N. Mahmoudian, "Effective turning motion control of internally actuated autonomous underwater vehicles," *Journal of Intelligent & Robotic Systems*, vol. 89, no. 1, pp. 175–189, Jan 2018. [Online]. Available: https://doi.org/10.1007/s10846-017-0544-3

[8] J. E. Naglak, B. R. Page, and N. Mahmoudian, "Backseat control of sandshark auv using ros on raspberrypi," in *OCEANS 2018 MTS/IEEE Charleston*, October 2018, pp. 1–6.

[9] B. R. Page, J. E. Naglak, C. Kase, and N. Mahmoudian, "Collapsible underwater docking station design and evaluation," in *OCEANS 2018 MTS/IEEE Charleston*, October 2018, pp. 1–6.