Highly Maneuverable Low-Cost Underwater Glider: Design and Development

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***Abstract*—This letter presents the design and potential impact of the developed Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE). The ROUGHIE is an open-source, highly maneuverable, and low-cost vehicle that enables rapid development and testing of new hardware and software. ROUGHIE is an internally actuated glider capable of performing steady sawtooth glides in shallow water down to 3 m, tight turns with a minimum radius of 3 m, and a minimum endurance of 60 h. The novelty of this study is twofold: 1) a rail-based design to facilitate modularity and ease of assembly and 2) an effective internal rotary mass mechanism to increase maneuverability and perform tight turns. The ROUGHIE design strategically uses 3D printed plastic parts in low stress situations, which allows extreme design flexibility and enables tightly packed modules that can be easily customized.**

***Index Terms*—Autonomous vehicle navigation, field robots, marine robotics, motion and path planning, underactuated robots.**

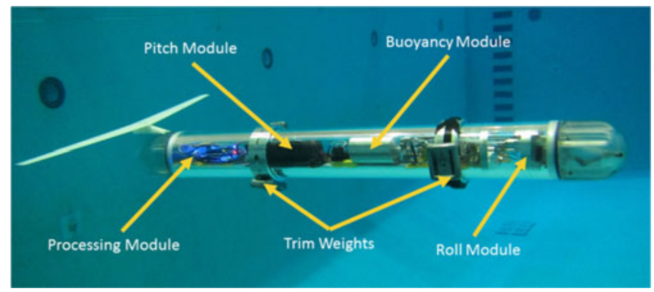

Fig. 1. The ROUGHIE's internal mechanisms: (a) The pitch module adjusts the desired pitch angle by moving the linear mass resulting in changing the center of gravity and creating a pitch moment. (b) The buoyancy drive pumps water in and out of the tank to change the glider's buoyancy. (c) The roll module pivots the main rail with respect to the hull, causing the hull (and hence the wing) to rotate.

I. INTRODUCTION

UNDERWATER gliders (UGs) are a subclass of autonomous underwater vehicles (AUVs) that travel through the water column by changes in buoyancy. The resulting sawtooth motion profile is slow but highly efficient, making gliders attractive for several oceanographic uses such as water quality measurement, mapping, and surveillance. AUVs have been under development for the past 50 years [1], culminating with the current state-of-the-art commercial UGs that excel in long endurance missions and deep water deployments.

Existing gliders are either commercial products or custom vehicles developed for specific missions by individual research labs. The commercially available gliders, sometimes referred to as legacy gliders [2], are highly capable open ocean vehicles with extensive operational history. These vehicles, while highly capable in open ocean, are prohibitively expensive for much of the research community and thus do not see extensive experimental deployments. The legacy gliders are also closed source vehicles, making adaptation to accommodate different sensor suites and control methods difficult if not impossible.

Legacy gliders are also not designed for maneuvering in littoral environments. Existing gliders actuate yaw through either the use of external rudder control or internal actuation of the glider's roll to induce turning motion, similar to a level turn in aircraft. External actuation has typically yielded the tightest turns such as in the gliding robotic fish [3] and Slocum with approximately 7 m turn radius [4], however, it is not ideal for glider deployments since the rudder increases drag, power consumption, and potential failure modes while maneuvering. Internal actuation has historically not been capable of the turns required for shallow water operation, with most internally actuated gliders achieving turn radii on the order of 30–50 meters [5]–[7]. So far the solution to increase this group of vehicles' maneuverability is to use hybrid actuation, where the designs blend actuators of AUVs and UGs in one vehicle, at the expense of efficiency. Thus, the current state of the art fails to provide a solution that increases the maneuverability of internally actuated gliders without the need for external actuation.

The ROUGHIE, shown in Fig. 1, has been developed at Michigan Technological University to create an internally actuated, highly-maneuverable glider capable of tight turns with a small spiraling radius. The ROUGHIE design focuses on moderate length endurance and littoral water deployment missions. Due to the space constraints of littoral zones, it was designed to be significantly more maneuverable than currently available UGs. In addition to its high maneuverability, the ROUGHIE features a fully modular design that allows easy integration with various sensors or processing platforms. Furthermore, open source control software built on an easy to use microcontroller makes the ROUGHIE an inexpensive collaborative platform to validate

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This paper has supplemental downloadable multimedia material available at http://ieeexplore.ieee.org, provided by the authors. The Supplementary Materials contain an MP4 file illustrating the circular maneuver of an underwater glider in shallow water. This material is 7.9 MB in size.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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TABLE I
COMPARISON OF EXISTING UNDERWATER GLIDERS

	Legacy Gliders [2], [8]				Lab-Scale Gliders		
	Seaglider [9]	Spray [10]	Slocum [4]	ROUGHIE [11]	Fòlaga [12]	Seawing [5], [13]	Grace [3], [14]
Overall Dimensions (cm)	30⌀ × 330	20⌀ × 200	21⌀ × 215	12.7⌀ × 130	14⌀ × 200	22⌀ × 200	15⌀ × 90
Mass (kg)	52	51	52	12.8	30	65	9
Depth Rating (m)	1000	1500	200	30	50	1200	No Data
Endurance (hours)	4800	7920	480	60	8	500(km)	No Data
Cost (USD)	70000	50000	70000	10000	No Data	No Data	No Data
Turn Radius (m)	28(int)	30(int)	7(ext)	3(int)	No Data(ext)	100(int)	0.5(ext)

Internally actuated designs are called out with an (int), while externally actuated designs are called out as (ext) in the turn radius row.

control strategies, serve as an educational model for control-based or marine robotics laboratories, and collect various water quality data in littoral environments. The ROUGHIE can also be used as a surrogate for more expensive gliders during controls development or as an operational glider for moderate endurance, shallow water deployments. The design is only a fraction of the cost of legacy gliders—on the order of $10K USD.

The ultimate goal is to provide a unified test platform to the community to experimentally validate new theories and algorithms without allocating a considerable amount of time and funding for platform development. This is in contrast with earlier efforts to independently develop in-house gliders; these *lab-scale gliders* are generally not available for use by the wider research community. Table I briefly compares characteristics of the legacy gliders and some lab-scale underwater vehicles with the ROUGHIE and serves as a numerical comparison between some current vehicles.

This letter is organized to present the ROUGHIE design and the role that it can play to advance underwater related research with its highly maneuverable characteristics. Section II details the design of the ROUGHIE, Section III discusses the vehicle's sensors and controller design, and Section IV presents the testing of ROUGHIE and its results. Section V summarizes the ROUGHIE design and future employment of ROUGHIE in broader underwater glider development.

II. Design Overview

The ROUGHIE can be broken into two major systems: the mechanical and the electrical systems. The mechanical portion of ROUGHIE provides the structure, hydrodynamic characteristics, and actuation to the glider. The electrical system provides power, sensing, and control to the different actuators in the ROUGHIE. The two systems combine to make the ROUGHIE a highly maneuverable, easy to develop glider for research purposes.

A. Mechanical Design

The ROUGHIE vehicle has been designed through a series of revisions over the past few years [15], [16]. The current revision of ROUGHIE, shown in Fig. 1, builds upon lessons learned over the years of building and testing new models. Fundamental to the ROUGHIE design is the novel use of a common mounting rail that serves three purposes: 1) Rigidly hold all modules

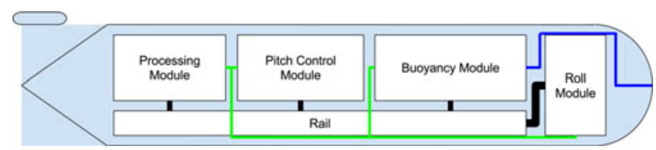

Fig. 2. The ROUGHIE's internal modular layout: black indicates physical connection, green is electrical connection, blue is plumbing connection. The modules can be replaced on the rail as required for the mission. The rail and attached modules rolls inside of the hull actuated by the roll module.

during gliding operation; 2) Serve as a cable tray and organize electrical interconnects between modules and the main control electronics; 3) Serve as an eccentric mass for roll and turning control. The rail is suspended between the front and rear end caps and mounted off center towards the bottom of the vehicle. This off center location enables the modules to be mounted on top creating a very large eccentric mass relative to total vehicle mass. With greater than 90% of all non-symmetric mass actuated by the roll system the ROUGHIE is capable of performing internally actuated roll maneuvers in excess of $+/-$ 60 degrees (currently limited by servo chosen, higher roll angles are possible including full roll over with different actuator choice). In addition to the rail based design, the ROUGHIE heavily utilizes 3D printed parts for low stress situations. 70% of all the custom made parts in the ROUGHIE are 3D printed. By using 3D printing we are able to minimize the cost of the vehicle, achieve highly complex geometries for specialized parts, and perform rapid design updates including adapting the modular layout to new configurations.

Starting at the front of the glider is the roll module as illustrated in Fig. 2. This module consists of the mounting hardware required to interface from the hull to a commercial-off-the-shelf (COTS) servo that has its shaft in line with the center of the hull. The servo attaches to the rail through a metal 3D printed connection arm that offsets the rail rotation from the hull center.

Mounted on the rail are the three different modules. Physical connections from the modules to the rail are accomplished with a universal mount that is integrated into the different 3D printed modules.

The first module mounted on the rail is the buoyancy module that provides locomotive force in the dive plane by driving changes in glider net buoyancy. The buoyancy module uses a COTS micropump capable of supporting up to 100 meters of head to pump water from the front port into the ballast tank. A normally closed solenoid valve is used in-line with the pump to interrupt the flow ensuring that water does not flow when the pump is not powered. Immediately behind the pump is the ballast tank and ballast tank mount. The ballast tank is a custom-machined cylinder capable of adjusting the ROUGHIE's net buoyancy by 375 g and is sealed by a 3D printed piston with a double o-ring sealing design to prevent jamming. 3D printing the piston allows the piston and draw wire attachment point to be integrated into one part that can be printed at very low cost. The ballast tank mount provides rigid attachment for the two draw wire sensors used for determining system center of gravity and ballast amount.

Aft of the buoyancy drive module is the pitch control module. The pitch control module consists of a 3D printed base plate that rigidly holds the linear mass, a 3D printed linear mass control plate, a linear bearing, a power screw, and a micro DC gearmotor. The linear mass is a 25.9 V 12.6 Ah lithium-ion polymer battery that serves as power source for the ROUGHIE and is attached to the linear mass control plate via adhesive. The control plate enables the battery to attach to the draw wire cable, linear bearing, and power screw nut. A linear bearing provides smooth motion between the linear mass control plate and the base plate which is controlled using the power screw. Actuation of the power screw is accomplished with a micro DC gearmotor through a high reduction gearbox.

Towards the rear of the ROUGHIE is the processing module. The glider control module is an electronics stack that builds upon a 3D printed mounting plate that interfaces the main rail mount design with the Arduino mounting bolt pattern.

The overall mechanical design of the ROUGHIE creates a vehicle that is capable of performing maneuvers such as turn with radius down to 3 m in addition to standard sawtooth glides, not previously accomplished by other internally actuated underwater gliders.

B. Electrical Design

The electrical system of ROUGHIE is also modular and designed to be highly adaptable and easy to modify. Central to the electrical system is the Arduino Mega. The Arduino Mega is a low cost, easy to program microcontroller with ample digital and analog input/outputs which can support an expanded sensor and actuator suite. In addition to these benefits the Arduino has a well established global community that constantly contributes to numerous open source libraries that can significantly simplify programming. The Arduino is also a very common first microcontroller experience for people new to the field, and thus has a well documented tutorial system that is very useful for new programmers. The Arduino is not the only option for microcontroller and other systems such as the BeagleBone Black can be substituted with minimal redesign.

As a research glider, we expect the ROUGHIE to be used by researchers across many disciplines. Thus, programming expertise is not a prerequisite for using our glider. We have developed a ROUGHIE-specific library to aid in the implementation of new controllers; the ROUGHIE library builds on our previous work of the multi-level controller [15]. The library based approach means that end users can understand and update the code as required for different missions without having to modify the low level implementation.

The electrical system only requires two custom printed circuit boards. One board sits atop the microcontroller while the other sits near the buoyancy drive pump. The board atop the Arduino derives all operating voltages from the battery using high efficiency DC-DC converters. We implement state of charge (SOC) circuitry to estimate the battery's SOC, allowing more accurate estimates of the glider's endurance; preliminary experiments suggest that the ROUGHIE's endurance is over 60 hours. We also implement other various custom circuitry to interface the peripheral actuators and sensors with the processing platform. The second board enables bidirectional pumping by switching the two outer phases of the pumps motor controller.

III. Navigation and Control

The ROUGHIE mission controller is a hierarchical navigational and control algorithm that autonomously navigates the underwater glider on different missions and is composed of two layers. The higher level of the mission controller manages the navigation and mission planning of the vehicle. The user has access to this layer of the mission controller through our custom User Interface (UI) software. The desired trajectory parameters are fed to the system through the UI, and the lower layer controls the internal actuators to satisfy the trajectory requirements calculated by the higher level controller. The user does not have direct access to this level during the mission. The controller compensates for the real-time error of control parameters by utilizing the data measured by the integrated sensors on-board ROUGHIE.

A. Sensors Integration

The mission controller utilizes sensory data provided by navigation and attitude sensors integrated in the ROUGHIE. Attitude and heading reference system (AHRS), GPS, pressure sensor, and sonar provide the essential data for the navigation control, while two draw-wire sensors, an inertial measurement unit (IMU), and the pressure sensor provide required data for the lower level controller. In addition to these sensors, ROUGHIE is capable of carrying up to 5 kg payload. This payload can be used to equip the ROUGHIE with ocean sampling sensors to collect data in lakes and harbors. Currently ROUGHIE is equipped with a Wetlabs ECO Puck fluorometer to measure the concentration of chlorophyll-a in open-water experiments.

The *pressure* sensor monitors the external pressure and is used to determine ROUGHIE's depth. It requires a 5 volt supply and provides an analog output proportional to the sensed pressure, which is read with one of the processing platform's analog inputs. This depth feedback is logged using the internal SD card data-logger and also can be used by the controller to determine the appropriate times to descend or ascend.

The *AHRS* and *GPS* are integrated in a single unit and are used by the ROUGHIE to estimate its current pose (yaw, pitch, and roll) and location, respectively. The pose data is used in the control loop for pitch, roll, and heading feedback, and the GPS

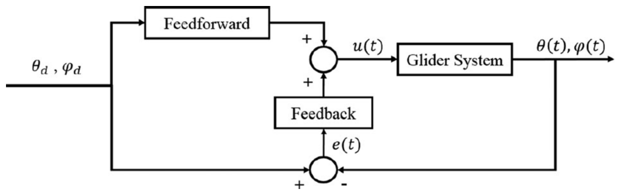

Fig. 3. Hybrid feedforward-feedback controller to control the pitch angle (θ) and roll angle (φ) of the glider. The controller begins by sending the actuators to an initial position calculated by the feedforward block, based on the desired pitch and roll angles, θ_d and φ_d, respectively. Attitude feedback from the IMU sensor is then used to compute the error, $e(t)$. Finally, the compensating signal, $u(t)$, is then sent to the actuators (pitch module, buoyancy module, and roll module) to achieve the desired pitch and roll angles. Depth is directly controlled by a bang-bang controller using the pressure sensor feedback to the buoyancy drive.

unit provides location data when the glider surfaces. This information is conveyed to the processing platform over a universal asynchronous receiver/transmitter (UART) serial communication interface.

The *sonar* is an Imagenex 852 Echo Sounder with maximum operating range of 50 meters and maximum operating depth of 300 meters, which is sufficient for shallow water missions. This unit requires approximately 1.5 Watts from a 24 V DC rated power supply. Sonar has been tested in the enclosed area but extensive tests in open waters is postponed to the summer of 2016 due to the harsh environmental conditions in the Upper Peninsula of Michigan.

The *draw-wire* sensors employed in the ROUGHIE are used to provide the control system with positional feedback of the ballast tank and the linear mass. These sensors use a small retractable cable to actuate an internal potentiometer, translating changes in linear motion to changes in resistance. We apply a voltage to the outer legs of the potentiometer and measure the voltage of the wiper with an analog input on the processor to determine the wire's position.

A COTS single-wavelength *fluorometer* has been used with the ROUGHIE to highlight the versatility of our modular design. This sensor was externally mounted to the glider using a custom aluminum casing. A waterproof cable connected the sensor to the internal electrical system through a waterproof bulkhead connector mounted on the rear rail end, and the sensor's output was measured by the processor's analog input. Results of the collected data is presented in Fig. 6 and will be discussed in Section IV.

B. Controller Design

The ROUGHIE mission controller uses navigation and attitude sensors along with internal actuation to control buoyancy, pitch, and roll to effectively navigate through the water. The ROUGHIE nonlinear dynamic model can be decoupled into horizontal and vertical planes to control dive and turn motion. The ROUGHIE uses a hybrid feedforward-feedback control approach described in [17] as a computationally affordable solution to the nonlinear control problem as shown in Fig. 3. This hybrid approach uses feedforward during nonlinear inflection events and feedback to reject disturbances during steady gliding. The heading controller in ROUGHIE is a novel extension of the hybrid controller to the roll system to achieve turning motion.

In ROUGHIE, two modules contribute to pitching motion, the buoyancy module and pitch control module. The buoyancy module causes the bulk of the pitching motion due to the forward location of the ballast tank while the pitch control module performs fine adjustments to the vehicle pitch and rejects disturbances. To perform sawtooth glides the buoyancy module pumps to a predetermined level and the pitch control module drives the pitch mass towards known positions for feedforward control. Once the ROUGHIE has established steady gliding motion due to feedforward, the feedback controller is enabled to compensate errors and finely tune the pitch angle and reject any disturbances that are encountered. Feedback control utilizes IMU feedback of the vehicle pitch angle to adjust the pitch mass location.

Controlling the heading angle of the vehicle in the horizontal plane is a more complicated task. In underwater gliders with no external actuator (rudder) like ROUGHIE, a roll induced heading angle approach is used, similar to a level turn performed by aircraft. By rolling the glider clockwise/counter clockwise, the hydrodynamic lift force applied on the wing from water induces a positive/negative yaw angle on dive/rise glide. This strategy is used to generate spiraling motion and turning maneuvers in ROUGHIE. The novel roll module in ROUGHIE is composed of a servo that pivots the common rail to the desired roll angle. As the common rail carries 90% of the internal mass of the vehicle, the roll moment created by this system is greater than classic internal roll mass mechanism used in this class of underwater vehicles, making ROUGHIE more energy efficient and highly maneuverable. The turn controller uses a reverse mapping feedback controller to control roll angle of the vehicle directly, which in turn affects the yaw angle of the vehicle. The roll controller is active for disturbance rejection and maintains the mean value of the roll angle as desired by the user in open water missions. The ROUGHIE roll mechanism can be an alternative or backup system for current AUVs' turning solutions since at low speed rudder can not efficiently control the heading.

IV. Performance Testing and Deployment of Roughie

ROUGHIE's performance characteristics have been validated through extensive experimental deployments. The platform has been tested for more than 200 hours in both the Michigan Technological University Student Development Complex dive tank and the nearby Portage Canal. The dive tank is 15.84 m long, 11.88 m wide and 4.27 m deep at its deepest point and has 10 water jets that induce local turbulence and currents that disrupt gliding operations. The Portage Canal is part of nearby Lake Superior with a typical depth of 10 m. The default method of glider navigation is based on a built-in dead reckoning control in which an estimate of depth-averaged currents is formed by the difference between expected and actual vehicle surfacing positions.

Early deployments utilized a pitch controller based on our previous work [15], though more recent experiments use an updated pitch controller based on the suggested hybrid feedforward-feedback controller [17]. This hybrid controller maintains the

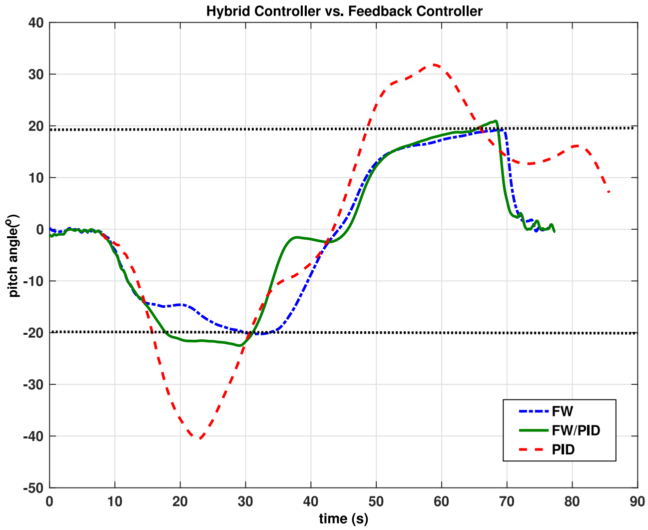

Fig. 4. Experimental control validation of the ROUGHIE: Pure feedforward (FW) control and pure feedback (PID) compared with hybrid feedforward-feedback. The hybrid controller approaches the desired glide angles rapidly and rejects disturbances. Desired glide angles for this test are $+/-20°$.

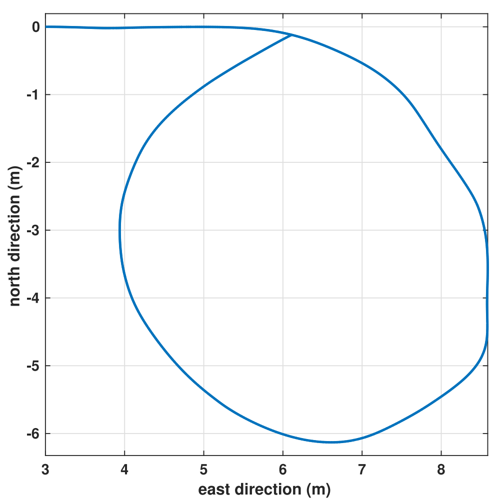

Fig. 5. Turning motion validation of the ROUGHIE during spiral testing. Motion trajectory in horizontal plane (top-down view) during pool testing. The ROUGHIE is capable of performing turn radius maneuvers as tight as 3 m.

desired pitch angle more effectively for shallow water operation. Fig. 4 illustrates the pitch controllers used in ROUGHIE. In addition to the sawtooth tests, the ROUGHIE's turning motion has undergone preliminary testing. Based on the initial turning results, the ROUGHIE is capable of turn radii down to approximately 3 m as shown in Fig. 5.

Furthermore, the ROUGHIE has been validated as easy to modify and program as we have implemented five different low level control methods: pure feedforward, pure PID feedback, pure fuzzy feedback, hybrid feedforward-PID feedback, and hybrid feedforward-fuzzy feedback. Fig. 4 shows an initial comparison between traditional PID control and hybrid PID with feedforward during nonlinear inflection events, details on this approach are available in another publication. The ROUGHIE

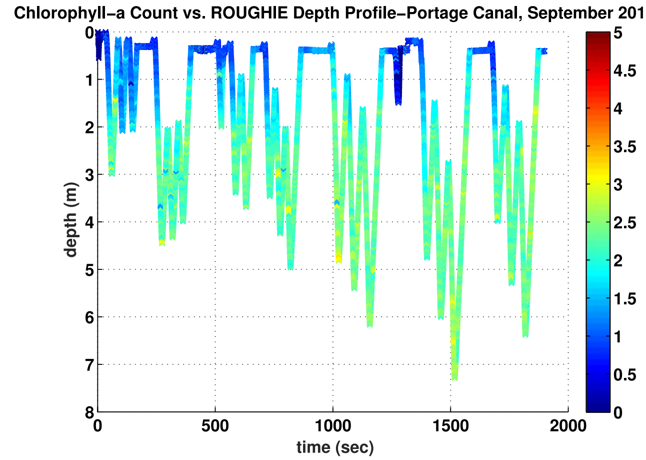

Fig. 6. Scientific payload validation of the ROUGHIE: ECO Puck deployment in Portage Canal. The ECO Puck measures chlorophyll-a concentration in water. The results collected reflect the expected concentrations for the test location.

is capable of validating many control strategies with minimal code modification thanks to the multi-level control approach.

The ROUGHIE has also been deployed with external payload sensors such as the Wetlabs ECO Puck fluorometer to validate its adaptability to accommodate different sensors. The external payload sensor is attached with a simple bolted connection and SEACON connector through the rear end plate for power and data connection. Data collected during ECO Puck deployment in the Portage Canal is shown in Fig. 6. During these tests the ROUGHIE was commanded to sample the water column over 30 minutes by completing clusters of three dives, increasing to depths up to 7 m.

V. Conclusion and Future Work

The design overview and initial test performance results of the Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) have been presented. The ROUGHIE is a low-cost, modular, and expandable underwater glider particularly useful for advancing marine research in littoral environments. Through extensive testing, it is confirmed that the ROUGHIE can function with a minimum endurance of 60 hours, a minimum turn radius of 3 meters, and a minimum operational depth of 3 meters. Should the ROUGHIE need to be deployed on longer or deeper missions, the design is scalable with an increase in cost. Its modular layout enables easy upgrades and drop-in repairs to be completed rapidly in the field. The low cost of ROUGHIE combined with its high maneuverability opens entirely new mission spaces to underwater gliders.

Additionally, the strategic use of 3D printed parts and the accessibility of the entire ROUGHIE platform allows rapid design changes to be iterated allowing experimental module configurations, control algorithms, and payloads to be tested. ROUGHIE offers good maneuverability characteristics in shallow water, where most control and sensor experimental tests are conducted by researchers.

Ongoing work includes characterization of the system performance in deep water and use of the ROUGHIE on different missions. Initial shallow water turning and maneuverability test results validate the turning capabilities of the ROUGHIE and are very promising, but deep water performance is still to be determined. Thus, we hope to more thoroughly test and characterize the ROUGHIE in deeper testing environments in the near future. Increasing single platform underwater capabilities such as obstacle avoidance and acoustic communication will also be part of the future focus. Multi-vehicle deployments with a fleet of three ROUGHIEs will occur in parallel to validate and expand coordination strategies for a variety of applications. The end result of this work is to provide a unified testing platform to the community for experimental validation of new theories and algorithms without allocating a considerable amount of funding to purchase test-bed. Our hope is to offer these vehicles to the communities that can benefit through partnerships for humanitarian missions.

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