ROUGHIE 2.0: Improving Performance Using a Modular Design Approach*

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***Abstract*— This work presents the lessons learned and critical updates to the Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE). The open water testing experience with the original ROUGHIE provides key insight to design and operation of small scale autonomous underwater vehicles. This paper is organized to share necessary considerations that will be crucial for future vehicle developments. It also describes ROUGHIE 2.0 design updates that include performance, reliability, and ease-of-use improvements. Due to the modular design of the ROUGHIE, each module was able to be upgraded as an independent system. The integrative system performance is then analyzed through exhaustive experimentation in controlled environments to prepare the ROUGHIE 2.0 for open-water deployments. The upgrades improve the ROUGHIE's functionality as a robust and user-friendly undersea scientific research infrastructure.**

Fig. 1: The ROUGHIE 2.0 in an unpainted carbon fiber hull. The hull is painted yellow to ease identification during deployment.

I. Introduction

Autonomous underwater vehicles (AUVs) have seen an explosion of growth in recent years with the ever improving computational power and efficiency of micro-controllers [1], miniaturization of actuators, and increasing energy density batteries [2]. One emerging technology in oceanographic measurement that lowers mission cost by increasing endurance is the underwater glider. Underwater gliders are propelled via changes in buoyancy, sometimes referred to as a buoyancy drive. Due to the lack of traditional propulsion devices, buoyancy driven gliders travel through the water in what is known as a *sawtooth pattern*. Sawtooth motion is highly efficient as energy is only expended during the inflection points between glides meaning that some gliders are able to extend missions from months to years over transoceanic distances [3].

Traditional underwater glider missions have focused on environmental monitoring with recent glider deployments expanding into areas such as mapping and surveillance. The legacy gliders [3]–[5] perform well for their design missions of long term deep ocean operation, however, performance and costs reduce glider deployments on high-risk or non-critical missions. Legacy gliders are mission specific, i.e. difficult to adapt to additional missions, due to their closed-source nature [6] making it costly to implement experimental control algorithms or integrate new sensors. The legacy gliders are also expensive, on the order of $100k for a basic configuration vehicle, thus limiting research deployments. These challenges limit glider usage on multivehicle and novel deployments such as under-ice exploration.

The Nonlinear and Autonomous Systems Laboratory[1] (NAS Lab) at Michigan Technological University has developed the Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE), Fig. 1, to increase glider maneuverability and bring reasonable performance to a newly accessible price point [6]–[8]. Integration of new sensors, new electronics, and new control algorithms are greatly eased on the ROUGHIE due to the open and modular nature of the vehicle. The ROUGHIE modules can even be rearranged to enable placement of equipment in non-standard mounting locations with relative ease due to the flexibility inherent in mounting on a common rail. Due to the flexible mounting abilities of ROUGHIE, high quality sensors can be attached at various locations throughout the vehicle to improve ROUGHIE's performance for specific missions. This paper presents the lessons learned through design, and recent updates to the ROUGHIE to improve performance and ease of use.

The remainder of this paper presents the original ROUGHIE in Sec. II, key considerations in the design process in Sec. III, the upgrades to the ROUGHIE in Sec. IV, and presents conclusions and future work in Sec. V.

II. The original ROUGHIE

The ROUGHIE (Fig. 2), presented previously in [6]–[8], is a small low-cost underwater glider for shallow water operation. At approximately 1.35 meters long and 16 kg it

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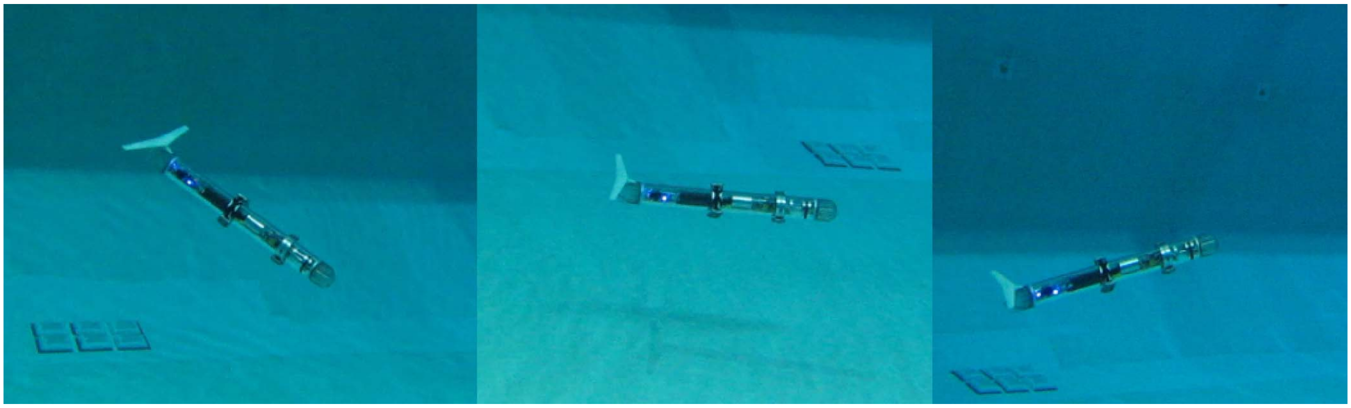

Fig. 2: Sawtooth pattern during pool testing of the original ROUGHIE. The ROUGHIE travels on a downward glide using the hybrid feedforward-feedback controller (left frame), then achieves neutral buoyancy (middle frame) before beginning an upward glide again using the hybrid controller (right frame).

is "man portable" and is able to be deployed by one person from a small craft with no additional launching hardware requirements. The ROUGHIE achieves shallow water performance through its use of a modular design building on a common mounting rail. Attitude control of the ROUGHIE is achieved by a system of moving masses; one sliding mass for pitch, one rolling mass for roll, and one adjustable mass for buoyancy (with significant effect on pitch). The novel roll mechanism consisting of approximately 90% of vehicle's weight leads to larger roll angles and consequently larger yaw moments than other internally actuated gliders, it also improves vehicle roll response for disturbance rejection. The ROUGHIE's novel internal roll mechanism endows it with an order of magnitude better turning performance than other internally actuated gliders as the ROUGHIE is capable of completing deep water turns with a minimum radius of 3 meters compared to the typical 30-50 meter radius [6], [9], [10].

The ROUGHIE is significantly lower cost than current gliders on the market [6]. Table I illustrates the main commercial off-the-shelf (COTS) components cost break down of the ROUGHIE 2.0. While being low cost is not a novel concept in the AUV market with platforms such as the SandShark developed by Bluefin Robotics [11], it is unique to the glider class since legacy gliders are on the order of \$100k+ USD and lab-scale gliders are generally not available for use. Despite its low cost, the ROUGHIE brings the functionality of existing gliders to extreme shallow waters (sub 10 meter). Table II outlines performance of the updated ROUGHIE design. The ROUGHIE can be equipped with various high quality scientific and navigational sensors, albeit with an increased cost to the vehicle.

These traits make the ROUGHIE an ideal platform for use in shallow water military and civilian applications. ROUGHIE is especially useful to the research community and can be used to accelerate control and underwater navigation development, reduce the cost of littoral surveying tools, and enhance undergraduate engineering and oceanography courses.

TABLE I: ROUGHIE Cost break down

Major COTS Components	**Cost (USD)**
Carbon Fiber Hull	450
BeagleBone Green Wireless	50
Pump	350
Battery	335
Pitch Motor	60
IMU	2910
Pressure Sensor	68
Draw Wire Sensors	370
Roll Servo	200
3D Printed Mounts	230
3D printed Wing	340
Major Component Total	5363

TABLE II: ROUGHIE Specifications

Length	Weight	Hull Diameter	Depth Rating	Turn Radius
1.35 m	16 kg	0.125 m	3-100 m	2.4 m

III. Design and Operational Considerations

The open water testing experience with the original ROUGHIE has led to some key observations for both design and operation of small scale autonomous underwater vehicles. Considerations include: 1) actuator speed, 2) actuator rigidity, 3) controller flexibility, 4) reliability, and 5) user-friendliness. These considerations can serve as general guidelines in the development process of new AUVs to prevent common pitfalls.

Actuator Speed: The pitch module actuator of the ROUGHIE takes five seconds to traverse its full range. This speed is sufficient for deep water operations where rapid change in the vehicle trajectory angle is not necessary. However, the time constraints associated with shallow water operation requires faster actuation to achieve acceptable performance. Fast actuation of the sliding mass allows rapid convergence to steady state flight.

Actuator Rigidity: The mechanical design of the pitch and roll modules of the ROUGHIE impacted performance. These modules had large machining and assembly tolerance that impacted actuation reliability. For example, the pitch module had a mass sliding on a single linear bearing. This linear bearing would flex and cause jamming issues under extreme loads. Switching to a more rigid system is required to eliminate these issues.

Controller Flexibility: The Arduino based controller on the original ROUGHIE was simple to use and easy to integrate, however it lacked the processing capability to implement computationally expensive controllers. In addition to the processing capabilities, Arduino does not support wireless data transfer as efficiently. During controller tuning it is vitally important to be able to update the controller parameters without disassembling the vehicle to access the on-board computer. Having higher processing capability and the flexibility to adapt to changing trends in the community will make ROUGHIE 2.0 an infrastructure for the future.

Reliability: Vehicle reliability is sensitive to many factors. First, unpredicted events occur while testing in open water resulting in vehicle hull loss incidents. Second, any internal failures will also result in vehicle loss. Finally, any sealing problems results in water ingress into the hull that will impact vehicle buoyancy and eventually cause electrical failure. These events need to be planned for to reduce cost of recovery missions. In August 2016 during untethered open water testing of the ROUGHIE a small electrical component failed in the buoyancy drive that caused the loss of the vehicle. The recovery process took 28 days and required manual retrieval, Fig. 3.

User-Friendliness: Due to the modularity of the vehicle, swapping parts and maintenance are possible in-situ and can be performed by the end-user. Although the assembly and maintenance process has been simplified by utilizing a rail-based design, the sealing method used was prone to failure due to human error. This was primarily caused by the sealing process that required replacing 8 o-rings, tightening 9 bolts, and making an internal plumbing connection. A robust mechanical design is required to ease the assembly process in order to reduce assembly complexity and eliminate the chance of poor operation due to assembly error. The user interface of the original ROUGHIE also presented issues due to the inability to reprogram without disassembling the vehicle thus impeding on-site controller updates. High-speed wireless communication will facilitate on-site controller development.

IV. System Upgrades and Performance

The major lessons learned during design and operation of the ROUGHIE informed the upgrades to the vehicle. The modular design approach of the original ROUGHIE enabled independent module design upgrades and integrative performance analysis. The ROUGHIE 2.0 features improved depth rating, faster pitch response, more robust roll response, improved reliability and user friendliness.

A. Internal Upgrades

Each module in the ROUGHIE 2.0 received an overhaul to enhance performance. These upgrades will improve: 1) pitch module speed and rigidity, 2) roll module rigidity and manufacturing, 3) buoyancy module control and depth, and 4) processing module computational power and ease of use. The upgraded ROUGHIE internals are shown in Fig. 4. The ROUGHIE 2.0 has passed bench testing stage with open water deployments and validation expected in the Summer 2017.

Pitch Module: The pitch module upgrade was mainly focused on increased rigidity to improve consistency during the transition between up and down glides. The mounting system for the sliding mass was changed from a single rail slider system to a dual rail system. The sliding mass position sensor was integrated into the one-piece mounting solution for the module. These upgrades improved the rigidity of the pitch mass to enhance its reliability. Additionally, a second pitch mass motor was added to increase the actuation speed and enable more advanced control methods. Initial test data shows that the new pitch module responds 220% faster than the original design.

Roll Module: The main change is the reorganization of the modules to place the roll module at the back of the vehicle. Additionally, the roll module received a mechanical design overhaul to decrease machining complexity while increasing rigidity. This design features a single clamping ring and mounting structure to support the same roll servo as before. The attachment to the rail is shortened and more supported compared to the original ROUGHIE. These changes, along with the choice of a more compact pressure sensor enables rolls up to $\pm 90°$. Previously, the roll angle was limited to $\pm 70°$. This range is now only limited by the current servo specification and could be extended to $\pm 180°$ and beyond allowing the ROUGHIE to accomplish full rollover maneuvers. Full rollovers could be used to experiment with uni-directional wings.

Buoyancy Module: The buoyancy module was rearranged to place the ballast system as far forward as possible relative

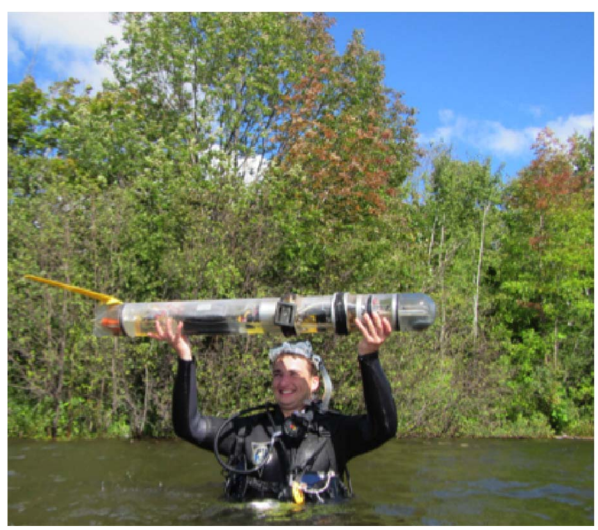

Fig. 3: Rescue mission, August 2016. The ROUGHIE was lost after a small electrical component failed. The recovery process took 28 days.

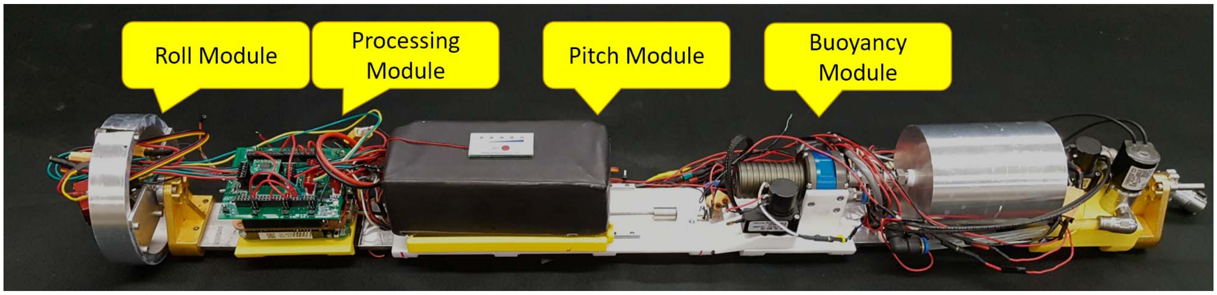

Fig. 4: Upgraded ROUGHIE internals. Each module received an overhaul to improve performance and usability.

to the glider center of buoyancy. Therefore, the roll module was moved to the rear of the vehicle. Maximizing the distance between the ballast and the center of buoyancy increases the pitching moment generated by the ballast and reduces the distance traveled by the pitch module. This lowers energy consumption and improves steady glide convergence rate. In addition, the pump and plumbing pressure rating was improved to support the new operational depth of 100 meters (subjected to validation).

Processing Module: The most significant upgrade to the ROUGHIE 2.0 is the switch to the BeagleBone Green Wireless to support implementation of the more complex control and navigational algorithms. The new processor is 64 times faster than the ATmega chip originally used. The BeagleBone Green Wireless features built-in WiFi which allows remote data collection and the ROUGHIE control code to be updated and run in a browser from any system with WiFi, including smartphones. Stacked atop the BeagleBone are two custom capes that manage all power conversion and data connections between the different modules and the main control electronics. Moreover, an emergency backup microcontroller has been implemented to control the emergency recovery system. This backup controller features completely independent power and actuation systems and is fully sealed to ensure functionality even in the event of catastrophic failure.

B. External Upgrades

The fuselage and the externals upgrades focused on reliability and user-friendliness. Based on the testing experience with the original ROUGHIE, the sealing mechanism and emergency recovery system were improved.

Sealing Mechanism: The ROUGHIE 2.0 utilizes a carbon fiber hull instead of the acrylic (or aluminum) hull in the original ROUGHIE. The swap to carbon fiber helps support deeper dives. More critically, it enables an improved sealing design based on a double piston seal due to the tighter tolerances available without costly precision machining. This double piston seal enables entirely bolt-free assembly and provides a more robust seal, easing the assembly process. Precision manufactured carbon fiber tubes ($\pm 0.15 mm \varnothing$) cost approximately the same as equivalent size aluminum tubes. The new sealing system also enables rapid prototyping of the low-cost non-pressure rated hydrodynamic end-caps on a small 3D printer. Experimental designs and sensor mountings can be manufactured for a few dollars per iteration.

Emergency Recovery System: A self-supportive system for immediate recovery of the vehicle in case of mission failure is desired. The old emergency recovery system, a pinger and manual recovery, has proven to be challenging when a glider is lost due to the difficulties of accurately locating the vehicle using a hydrophone in the dynamic underwater environment. Assuming the vehicle is located, either ROVs or divers must then go to recover the vehicle manually. This manual search and rescue process is costly and takes significant time. For example, in August 2016 a ROUGHIE was lost and the recovery process took 28 days.

Currently, an upgraded emergency recovery system is being developed which will utilize a secondary control board with backup power and actuation. The emergency recovery system can be activated by several different triggers. First, if the communication link between the primary and secondary controller is broken (indicating loss of system control), the secondary controller will act as a watchdog and trigger the recovery system. As an additional trigger, two leak sensors are integrated into the vehicle. If the leak sensors detect a leak, the recovery system can be triggered prior to vehicle flooding. Two sensors are used to provide redundancy against false positives and to determine the amount of fluid inside the hull.

Two potential systems to solve the self-rescue problem are a high visibility compressed-air lift bag [12], and a recovery buoy with an on-board GPS transmitter [13]. Both methods are being evaluated for use on ROUGHIE along-side the current echo-locator system. A lift bag uses watertight fabric to store the volume of air needed to make an object neutrally buoyant. At the current depth rating, this lift bag would need to contain 16.3 liters of air to ensure ROUGHIE's assent in a worst case, fully flooded scenario. A recovery buoy is a small buoyant object on the end of a long line that is sent to the surface. Once at the surface either emergency system could be used to transmit a GPS signal of its current location which would allow for easy recovery. Both of these modules allow the ROUGHIE to employ self-rescue actions at minimal cost.

V. Conclusion & Future Work

This paper presented the ROUGHIE 2.0 design based on the operational experience with the original ROUGHIE. During the testing and development process, the following upgrades were identified as critical to improve system reliability, user-friendliness, and functionality. The goal is to increase 1) actuation speed and rigidity of the pitch module, 2) rigidity and capability of the roll module, 3) strength and performance of the buoyancy module, 4) computational power of the processing module, 5) reliability of sealing and ease of assembly, and 6) emergency recovery system robustness. These upgrades enable the ROUGHIE to achieve faster pitch response at greater efficiency, expand the operational depth to 100 meters, increase user-friendliness, and enable reliable self-rescue in the event of major failures.

The ROUGHIE 2.0 is a capable operational vehicle based on initial constrained pool testing. During the Summer of 2017, extensive open water testing is planned including long duration missions in Lake Superior. During these deployments, the performance of the ROUGHIE will be evaluated on missions over 7 days. The ultimate goal will be to transit across Lake Superior to Isle Royale while collecting water quality data for the Michigan Tech Great Lakes Research Center. Summer 2017 plans also include the fleet oriented deployments of the low-cost ROUGHIE 2.0.

In addition, a newly developed motion control architecture that efficiently links steady wings-level and turning flights to create optimal paths for underwater navigation will be implemented and validated. The ROUGHIE 2.0 will be tested to characterize turning motion. The resulting verified new flight patterns will open new deployment opportunities for underwater gliders in high-risk areas.

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