A Novel Roll Mechanism to Increase Maneuverability of Autonomous Underwater Vehicles in Shallow Water*

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***Abstract*— This paper presents a novel roll mechanism and an efficient control strategy for the roll and pitch of internally actuated autonomous underwater vehicles (AUVs) including most underwater gliders (UGs). The proposed design and approach increases maneuverability which is essential for operating in shallow water or crowded harbors. The design is implemented on Michigan Tech's research UG ROUGHIE (Research Oriented Underwater Glider for Hands-on Investigative Engineering) and the performance is validated. The experimental results demonstrate that ROUGHIE is capable of tight turn radii down to approximately twice the vehicle length in shallow water.**

I. INTRODUCTION

Gliders maneuver in water through the use of either internal or external actuators. Internal actuation reduces potential failure due to damage or fouling and removes any rudder induced drag, making it particularly attractive for gliders. However, most internally actuated gliders such as the Seaglider and Spray are optimized for open ocean deployments [1], [2] and in turn have typical turn radius capabilities on the order of 30-50 meters [3]–[5]. Other gliders optimized for high maneuverability in littoral waters have avoided internally actuated designs and use external rudders or tails to achieve tight turns, such as the Slocum and the Gliding Robotic Fish [3], [6]. A third approach, used by underwater gliders such as Liberdade and X-Ray, is based on a flying wing design combined with multiple external actuators to achieve maneuverability, but the increased size of the hull results in higher energy consumption due to drag [7].

The Nonlinear and Autonomous Systems Lab at Michigan Tech has developed the Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) that utilizes a novel internal roll mechanism, blending the inherent reliability of internal actuation with the high maneuverability required for littoral water deployment. The ROUGHIE's rail based design enables the vehicle to roll in excess of $\pm 60^o$, resulting in a minimum turn radius of 2.4 meters in shallow water, or an estimated deep water turn radius of 1.5 meters, which is unprecedented for an internally actuated vehicle with the body length of the ROUGHIE (1.2 m).

In addition, the ROUGHIE is low-cost, easy to modify, and features an open infrastructure that allows easy collaboration for research groups that have limited access to legacy gliders. It is capable of being adapted to diverse mission spaces and payloads up to 5 kg, and can serve as surrogate for controls development of any internally actuated glider. The roll mechanism used by ROUGHIE can also be translated to other torpedo-shaped AUVs for increased reliability and maneuverability.

The remainder of this paper discusses the ROUGHIE design and modelling in Section II, the motion controller in Section III, experimental results in IV, and concludes in Section V.

II. DESIGN AND MODELLING

A glider is modeled as a rigid body with moving point masses along the longitudinal and transverse axis to maintain the glider's motion. In ROUGHIE, these point masses include the hull (m_h), linear sliding mass (m_s), buoyancy mass (m_b), and rotary mass (m_r). Hence the total mass of the glider is $m_t = m_h + m_b + m_s + m_r$. If we denote the mass of the displaced fluid as m_f, the net buoyancy can be calculated as $m_0 = m_f - m_t$. The vehicle is negatively (positively) buoyant if m_0 is negative (positive).

The modular design, shown in Fig. 1, realizes these point masses as different actuated modules, all mounted to a common rail. The common rail provides structure to the modules, acts as a cable guide for electrical interconnects between modules, and serves as eccentric mass for the roll mechanism.

The processing module in this design manages the glider power distribution, payload data collection, control strategies, and navigation. It is based on the Arduino Mega platform that allows for easy expansion and global development through the use of commercial expansion boards called "shields" and open-source software. The ROUGHIE processing module uses three shields to operate: two commercial (XBee radio communication and SD data logging) and one custom (electrical breakouts, motor drivers, voltage converters, etc).

Just forward of the processing module is the pitch module which actuates the linear sliding mass (m_s) forward and backward to adjust the center of gravity (C_G). The pitch module includes the 2.2kg system battery and can adjust its position, $\mathbf{r}_s$, up to 8.5cm; $\mathbf{r}_s$ is the input to pitch controller to adjust the pitch angle θ. Ultimately, the vehicle velocity $V =$

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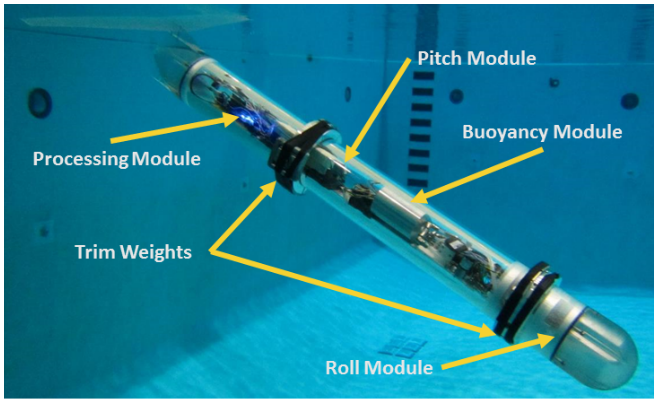


Fig. 1: The ROUGHIE's internal mechanisms. The pitch module adjusts the desired pitch angle by moving the linear mass resulting in changing the center of gravity and creating a pitch moment. The buoyancy module pumps water in and out of the tank to change the glider's buoyancy. The roll module pivots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

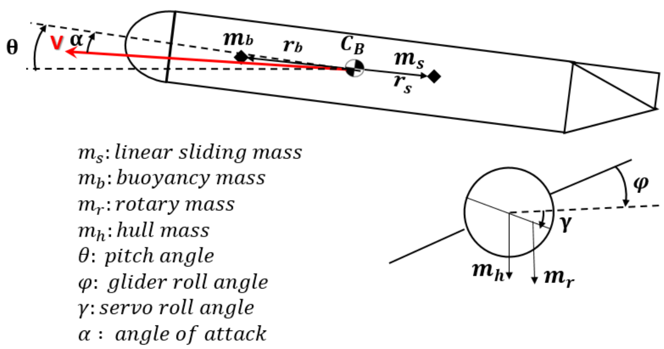


Fig. 2: Mass distribution, pitch angle orientation, and location of center of gravity and center of buoyancy.

$\sqrt{v_1^2 + v_2^2 + v_3^2}$ and pitch angle θ determine its trajectory, and motion in the vertical plane obeys:

$$\dot{x} = v_1 \cos\theta + v_3 \sin\theta, \text{ and} \tag{1}$$
$$\dot{z} = -v_1 \sin\theta + v_3 \sin\theta. \tag{2}$$

Fig. 2 illustrates these quantities as well as the vehicle orientation and mass distribution.

Forward of the pitch module is the buoyancy module consisting of a ballast tank, micro pump, and associated electronics. In this design, the buoyancy module serves as the locomotive engine of the ROUGHIE as well as its primary source of pitching motion due to its forward location in the vehicle. The module's mass, m_b, is used as the buoyancy controller's input and is changed by pumping water in and out of the buoyancy tank. When the tank fills, it causes a pitching moment on the ROUGHIE due to its distance from the C_G, $\mathbf{r}_b$. This causes the vehicle to pitch down to approximately the ideal pitch angle, set to 20^o in our preliminary pool tests. Similarly, when the tank empties it causes an upward pitching moment resulting in the vehicle pitching toward the ideal pitch angle. The pitch angle is more finely adjusted by the pitch module, ensuring that the vehicle reaches the desirable glide angle.

The hydrodynamic forces and moments affecting the glider motion are estimated by

$$D = (K_{D0} + K_D\alpha^2)(v_1^2 + v_3^2), \text{ and} \tag{3}$$
$$L = (K_{L0} + K_L\alpha^2)(v_1^2 + v_3^2), \tag{4}$$

where L is the lift force and D is the drag force as shown in Fig. 2. The K coefficients are constant and depend on glider geometry; these coefficients also affect the ballast module's mass,

$$m_b = (m_f - m_t) + \frac{1}{g}(-\sin\xi(K_{D0} + K_D\alpha^2) + \cos\xi(K_{L0} + K_L\alpha))V^2, \tag{5}$$

where $\xi = \theta - \alpha$ is the vehicle glide angle.

At the front of the ROUGHIE is the roll module which is responsible for controlling the roll angle ϕ, turn, and heading angle ψ of the vehicle in operation. The roll module uses a servo to rotate the common mounting rail, pivoting all modules attached to the rail relative to the vehicle's hull. This mechanism allows us to use essentially all of the glider's internal mass to create the roll moment, leading to tighter turns and a faster roll response. The ROUGHIE is capable of a complete rollover depending on the servo chosen, however, in the current revision it is limited to $\phi = \pm 60$ degrees. Henceforth there are two roll angles that will be described: the internal roll angle (γ), which also serves as the control input to the roll controller, and the vehicle's roll angle (ϕ). The internal roll angle is the angle to which the servo is driven, while the vehicle roll angle is the resulting angle measured by the ROUGHIE's internal attitude and heading reference system (AHRS). We calculate the rotary mass' distance to vehicle's C_G by

$$\mathbf{r}_r = r_{rx}\mathbf{x}_b + R_r(\cos(\gamma + \pi/2))\mathbf{y}_b + \sin(\gamma + \pi/2)\mathbf{z}_b). \tag{6}$$

Then the spiraling motion model of ROUGHIE is defined as

$$0 = \mathbf{P} \times \mathbf{\Omega} + m_b g(\mathbf{R}_{ib}^T \hat{\mathbf{k}}) + \mathbf{F}_{ext}, \text{ and} \tag{7}$$
$$0 = \mathbf{Q} \times \mathbf{\Omega} + \mathbf{P} \times \mathbf{V} + (m_r\mathbf{r}_r + m_s\mathbf{r}_s + m_b\mathbf{r}_b)g \times (\mathbf{R}_{ib})^T\hat{\mathbf{k}}) + \mathbf{T}_{ext}, \tag{8}$$

where $\mathbf{Q}$ and $\mathbf{P}$ are the vehicle's generalized translational and angular momentum, respectively, $\mathbf{\Omega}$ is glider's generalized angular velocity, and $\mathbf{F}_{ext}$ and $\mathbf{T}_{ext}$ are the external forces.

Spiraling motion is initiated by the sliding mass travelling to its feedforward position $\mathbf{r}_s$, inducing the initial pitch angle. The rotary servo then pivots the common rail to γ, inducing the yaw moment. We also assume that the rate of the net buoyancy is constant ($\dot{m_b} = 0$) during the spiraling motion. The spiraling motion of the glider is well studied in [8], [9].

ROUGHIE is designed to carry up to 5 kg of payload and in the absence of the payload a trimming belt is used. In general, ROUGHIE is trimmed employing the ballast tank, the linear sliding mass, and this trimming belt. At the

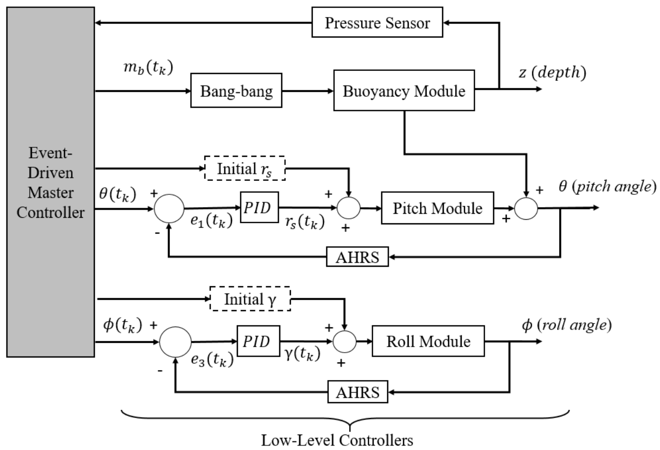


Fig. 3: Motion control structure contains feedforward-feedback pitch control, bang-bang depth control, and feedforward-feedback roll control.

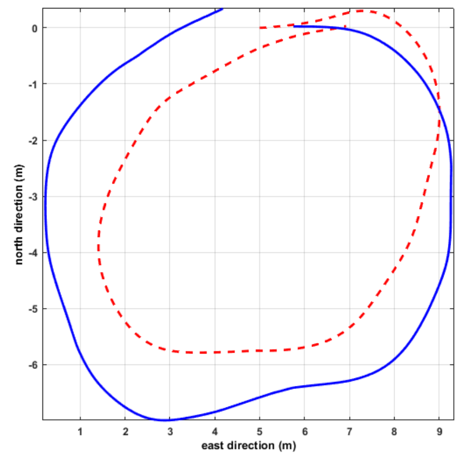


Fig. 4: Circular maneuver in presence of roll controller shown in dashed red line. By achieving the target vehicle roll ($\phi = 40^o$), ROUGHIE achieves a tighter turn radius when the PID controller is activated. The blue circle depicts the pure feedforward approach.

beginning of each deployment, the ballast tank is filled half way, the linear sliding mass is moved to its center position, and the external trimming weight is adjusted to maintain a neutrally buoyant state at the surface.

III. Motion Controller

The ROUGHIE control system is built upon the multi-level controller described in our previous work [10]. This system's high-level event-driven master controller is an intermediate controller between the user and the low-level controllers that actuate the ROUGHIE's modules; it translates the desired glide parameters into usable information for the low-level controllers. The low-level controllers then manipulate the pitch, buoyancy, and roll modules. This work features an updated controller whose newest revisions extend its capabilities to integrate roll control, allow better dive plane control, and require less interaction with the user.

Fig. 3 describes the low level controllers used. Depth control is achieved with simple bang-bang control on pressure feedback; fine pitch control is completed using a hybrid feedforward-feedback approach on the ballast system and linear sliding pitch mass; and roll control is achieved using either a feedforward or a feedback approach (the type of controller is selected by the user). Feedback for both pitch and roll is provided by the onboard AHRS.

A. Pitch Controller

Validation of the ROUGHIE design as a fully functioning underwater glider required implementation of a pitch controller that could effectively actuate both the buoyancy and pitch modules in concert. A hybrid feedforward-feedback controller was chosen for the dive plane as it is computationally affordable, easy to implement and alter for first time users, and decreases the time to reach steady state over more traditional pure feedback controllers [11]. The hybrid controller relies on feedforward principles during nonlinear inflection events between steady glides. This enables the system to rapidly approach its ideal glide angles by driving the internal masses to known setpoints for steady flight conditions. The hybrid controller then switches to using a PID feedback control during steady state glides for disturbance rejection. More advanced controllers can be implemented through simple code changes and the ROUGHIE is capable of supporting multiple controllers that are user selectable during mission configuration.

B. Roll Controller

The ROUGHIE roll controller operates with two distinct modes: either feedforward mode or feedback mode. Feedforward mode drives the roll control module's servo to a predefined internal roll angle, γ. This mode is primarily used for system identification and experimental inverse mapping between the servo's shaft angle and the glider's roll angle. Feedback mode maintains a constant vehicle roll angle, ϕ, by adjusting the servo's shaft angle based on PID feedback control from the AHRS. The majority of ROUGHIE's operation utilizes feedback mode since it achieves target roll angles quickly and rejects most environmental disturbances. Fig. 4 illustrates the difference in circular maneuver operation when the roll PID controller is activated vs pure feedforward approach. The feedback controller achieves the desired roll angle while the feedforward controller fails to achieve the desired angle and instead rolls to $\phi = 35^o$ due to the small non-actuated, non-symmetric mass in the ROUGHIE trim system. Fig. 5 demonstrates testing the roll feedback controller in a static roll test scenario. The PID controller achieves desired roll angles quickly and rejects most disturbances.

IV. Experimental Results

ROUGHIE deployments thus far have been primarily focused on system characterization and testing. Glider test-

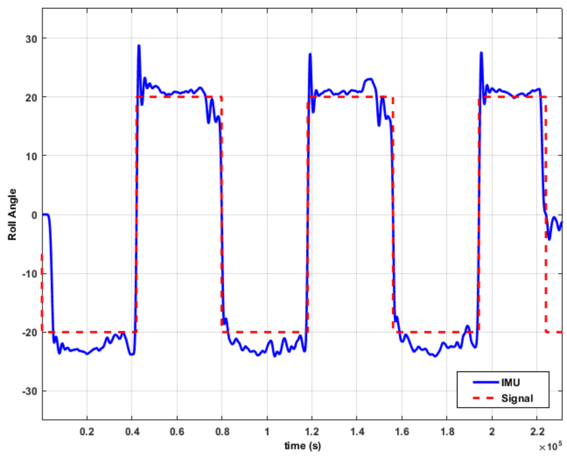


Fig. 5: Roll test to characterize the ROUGHIE roll feedback controller. The commanded roll angle (dashed red line) is compared with measured vehicle roll angle, ϕ (blue solid line). The overshoot at the beginning of each cycle where the vehicle is rolled to the positive angle is due to the external asymmetric trimming weight. The PID roll controller compensates for the external roll moment and adjusts the vehicle roll to 20^o.

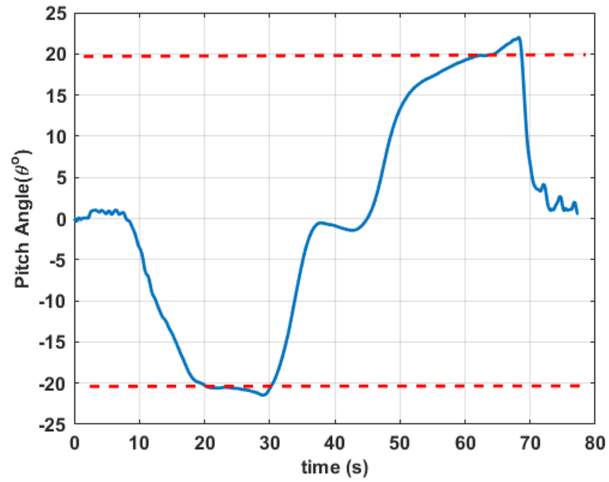


Fig. 6: Hybrid pitch controller. The controller drives the vehicle to $\phi = \pm 20^o$ as commended by user. Controller behaviour on up glide is slightly different from down glide due to the vehicle's momentum at the transition point. In the hybrid controller we try to rectify this over shoot by adding a neutrally buoyant state at the transition as shown in the figure when the pitch angle reaches to zero.

ing initially focused on dive plane control and has since evolved into testing the turning capability of ROUGHIE in shallow water. Most of the testing has been completed in the relatively shallow dive tank at the Michigan Technological University Student Development Complex that is 15.84 m long, 11.88 m wide, and up to 4.27 m deep in the deepest part of the diving well.

A. *Vertical Plane Results*

Dive plane verification of the hybrid feedforward-feedback controller has been completed primarily in pool tests and experimentally demonstrated in Lake Superior. With the hybrid feedforward-feedback controller the ROUGHIE is capable of achieving steady state motion in the dive plane while operating at the shallow depth of our pool. Results of one of the pool tests are shown in Fig. 6. The hybrid controller enables ROUGHIE to rapidly reach the target glide angle and reject disturbances in operation. Rapidly achieving target glide angles is a requirement for ROUGHIE's operation in shallow water.

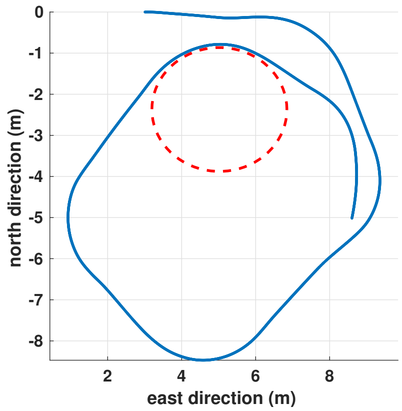
B. *Roll/Turn Results*

Roll/turn verification of the ROUGHIE's capabilities has been completed in the Michigan Tech pool through circular motion path tests within 3 meters from the surface. The shallow depth restriction is an absolute worst case scenario for an underwater glider, as it is not deep enough for most motion controllers to achieve steady state in the dive plane, let alone in turning motion. During testing the ROUGHIE first achieves steady state glide, then rolls to a predetermined roll angle using the roll feedback controller to initiate a turn. Due to the shallow operational environment of the pool, the ROUGHIE operates from 0 to 3 meters depth to minimize chance of collision. Fig. 7 shows the ROUGHIE performing a $\pm 35^o$ roll angle circle in shallow water. In Fig. 7a, a top down view of the motion profile demonstrates the difference between shallow water turning capabilities and estimated deep water turning capabilities. The blue line traces the ROUGHIE's motion which completes a turn with overall radius of 4 meters while in shallow water. Of note on the blue profile is the distinction between straight and curved sections. The current ROUGHIE controller requires steady state gliding conditions before enabling turning motion, ensuring that the glider enters true turning flight and not sideslip conditions. If the turning motion is isolated, the steady state or deep water performance of ROUGHIE is estimated to be 1.5 meter turn radius for the 1.2 meter ROUGHIE at 35 degree roll angle.

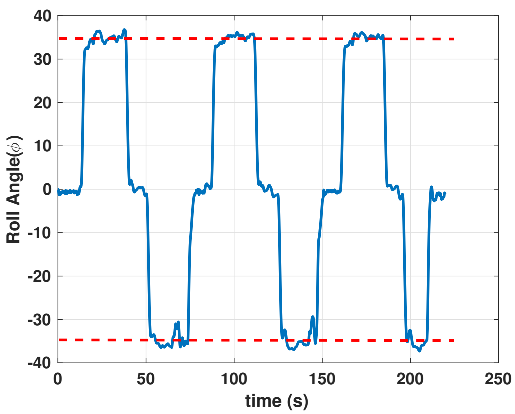
Fig. 7b demonstrates the ROUGHIE's roll feedback controller in operation for the previously described circular motion test. The feedback controller maintains the vehicle's roll angle through disturbances and rapidly achieves new target angles. Through the circular motion test ROUGHIE changes target angles several times between $+35^o$, 0^o, and -35^o. $\pm 35^o$ is used during steady flight conditions to drive the turning motion while 0^o is used during transition between glides.

V. Conclusion and Future Work

The novel roll mechanism described achieves best-in-class tight turn radius with an experimentally validated 2.4 meter turn radius in shallow water and estimated 1.5 meter turn radius in deep water. The internal roll mechanism creates the



(a) Circular path



(b) Roll angle $\phi = \pm 35^o$

Fig. 7: ROUGHIE performs a multi-helix path in a circular maneuver. a) top view of the circular maneuver completed in two glides shows ROUGHIE's tight turn, the red circle is an estimate of ROUGHIE's spiraling motion in deep water. b) roll angle during multi-helix maneuver, commanded roll angle is $\phi = \pm 35^o$ which with PID roll control, ROUGHIE was able to achieve the steady state very quickly.

required turning moment with less effort than external roll mechanisms, thus it is more energy efficient. We report the data collected during our water tests and discuss the different aspects of the new mechanism and its effect on the vehicle motion. This mechanism is useful for both underwater gliders and AUVs, especially at lower speeds when an external rudder is less effective in maneuvering the vehicle. The ROUGHIE's modular design is adaptable to diverse mission spaces and it can serve as development surrogate for more expensive legacy glider deployments.

Future work with the ROUGHIE will include validation of navigation and heading control in open water, fleet deployment, and environmental data collection. Open water testing will allow for experimental verification of the 1.5 meter spiral radius in steady state, since the operational depth is not limited as it is in pool tests. The deeper water will allow more comprehensive tuning of the motion controllers in steady state.

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