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Low Cost Underwater Gliders for Littoral Marine Research

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Abstract— **Current off-the-shelf underwater gliders (UGs) are large, heavy, expensive, and difficult to modify, both in hardware and software, which limits their use for multi-vehicle coordination experiments and deployment in high-risk environments. To address these challenges, the Nonlinear and Autonomous Systems Laboratory (NAS Lab) at Michigan Tech has designed two types of UGs for concept development, testing, and problem solving, and additionally, for scaffolding advanced interest and education in engineering. The first, a Glider for Underwater Presentation and Promoting Interest in Engineering (GUPPIE), nationally targets high school students and undergraduates to provide these students a UG platform for hands-on experience in concept development, testing, and problem solving. The second platform is a Glider for Autonomous Littoral Underwater Research (GALUR). At 10% of the cost of current models, the GALUR was designed to serve as a low cost multivehicle control testbed for disparate research groups who need to test and validate control algorithms. Still a highly-maneuverable UG, the GALUR allows researchers to address underwater communication issues by implementing control strategies for individual and multiple vehicle underwater data collection and mapping. Through the process of developing and testing these two UGs, the research team is ultimately working toward their long term goal of developing a fleet of low cost highly maneuverable underwater gliders. This paper details the challenges and milestones of the development process, and outlines the future research trajectory and goals.**

I. INTRODUCTION

In recent years, the use of remote sensing techniques from satellites has significantly advanced ocean surface studies [19]. However, only limited measurements can be made under the oceans surface with surface drifters and deep ocean floats [6]. Therefore, marine scientists are relying more on autonomous underwater vehicles (AUVs) to gather critical oceanographic data. In addition, AUVs are able to monitor a large volume at a fraction of the overall cost of other systems. Despite these benefits, there remain many challenges with current AUVs that greatly limit their potential [19], particularly limited endurance. Buoyancy-driven underwater gliders (UGs) by contrast, have proven to be effective for long-range, long-term oceanographic sampling. UGs operate at low speeds, typically less than 1 knot [20], compensating for limited speed with diverse sampling envelopes, traveling over 3600 miles in one trip [18] and to depths of 4000m [13]. Typical legacy glider (Slocum [18], Seaglider [4], or Spray [14]) missions include measuring temperatures, salinity, turbulence, zooplankton biomass, and other measurements in open water with low power requirements [17]. The navy has also investigated UGs for multiple purposes, including the tracking of diesel submarines, fleet positioning, littoral zone observation, and mine detonation [20]. Many of the potential applications, however, have additional requirements above those that informed the design of the oceanographic sampling legacy gliders. For example, underice polar data collection is complicated by an inability to get GPS localization for many sequential dives [15]. Task-oriented missions, such as, naval submarine tracking, pipeline monitoring and mine detonation require accurate underwater positioning. Many of these new applications involve high risk environments, where accidents or enemy action may disable a glider.

UGs normally operate in a stable, steady motion with no propulsive power consumption. Altering the buoyancy through intake or expulsion of water causes vertical forces, which can be translated to lateral motion via wings, producing a triangle-wave motion. This path enables gliders to sample at varying depths, ranging from littoral to the abyssopelagic zones, at extended distances. To navigate, UGs shift internal masses, changing their center of gravity, which execute rolls and yaws. These motions can be exploited with dynamic control systems to enhance locomotive efficiency by reducing the energy expended for guidance and control [10] [11]. The glider can be periodically localized by communicating with GPS satellites when UGs temporarily surface between dives. This can then be used to navigate to achieve the glider's mission. Extensive work regarding control systems, dynamics, path-planning, and fluid analysis of UGs has been developed [2], [8], [7], [5] and [10].

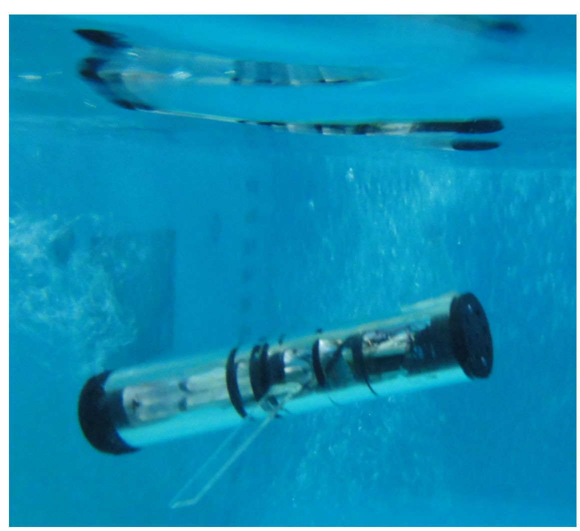

Fig. 1. The GUPPIE in Dive Transition

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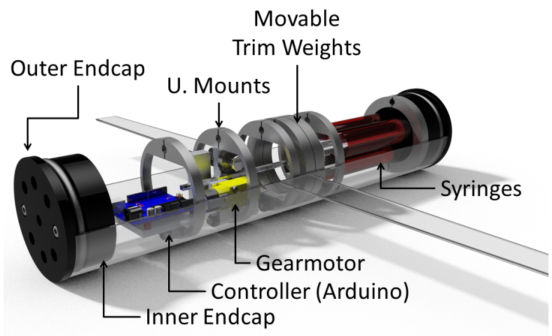

Fig. 2. 3D-model of GUPPIE

Metric	Value
Dimensions (cm)	10.3 (d) x 50.2 (l)
Wingspan (cm)	60.9
Total Mass (kg)	4.15
Payload Mass (kg)	0.99
Endurance (min)	25.8
Maximum Depth (m)	3.0
Glide Angle (degrees)	45
Displacement (mL)	160
Cost (USD)	$1000
Manufacturing Time (hr)	80

TABLE I
GUPPIE CHARACTERISTICS

Recent research has focused on cooperative and biomimetic control of glider "schools" to improve measurement quality and robustness [9] and [1]. Unfortunately, the high price and difficulty of programming and modifying hardware of current underwater gliders prevents them from being a viable candidate for high-level collaborative control research.

To address these challenges, the Nonlinear and Autonomous Systems Laboratory (NAS Lab) at Michigan Tech is designing and developing inexpensive UGs for different purposes. This paper presents the design and modeling of two types of UGs. First in Section II, the educational glider called GUPPIE, a Glider for Underwater Presentation and Promoting Interest in Engineering (see Figure 1), is described. GUPPIE is developed using commonly available components such as syringes for buoyancy control and a hull made of acrylic for easy analysis. It is an affordable design to teach students about glider mechanics, hydrodynamics, trimming, mobility in water, diving and surfacing characteristics, and the transitions between the cycles. The second design is called GALUR, the Glider for Autonomous Littoral Underwater Research, and will be discussed in Section III. The GALUR is designed as a highly maneuverable, low-cost UG for use in near-shore task-oriented autonomous control system testing and multivehicle coordination experiments. With a sophisticated control system, modular sensor configuration, and efficient hydrodynamic configuration, GALUR will enable implementation and validation of multi-vehicle coordination algorithms. The low price of GALUR makes unit loss or failure relatively insignificant allowing for more aggressive research to be done in volatile environments or with speculative control strategies than is possible with existing platforms. Finally, in Section IV future plans are discussed.

II. DEVELOPING THE EDUCATIONAL UNDERWATER GLIDER

The GUPPIE was designed to provide a reliable, adaptable educational platform and to prototype sealing and control mechanisms for a shallow-water, multivehicle control testbed. These goals implied the use of common, lightweight, durable components, and an easy and inexpensive manufacturing process. The GUPPIE also required sufficient endurance for effective demonstrations and tests.

For easy demonstration of glider operation and debugging of control mechanisms, a clear acrylic hull was used. Buoyancy control was achieved using syringes, to model the longitudinal piston buoyancy weight later used in the GALUR. The control system for the GUPPIE had to be simple, easy to understand, and a good educational tool at varying knowledge levels. To meet this need, the GUPPIE was designed to accommodate two different control systems: a simple bang-bang control system with limit switches, and a more sophisticated potentiometer for linear and nonlinear feedback control. An Arduino UNO was used for the controller, to allow for easy adaptation and programming by students of all levels, and to provide sufficient processing power for initial algorithm tests.

The battery pack usually accounts for a significant fraction of the weight of an underwater glider. In this case, however, long endurance was not a significant design consideration, so a Li-ion battery pack with an actual endurance of 30 minutes was selected. Figure 2 illustrates the components and Table I shows the characteristics of GUPPIE.

The actual hydrodynamic parameters for GUPPIE have not yet been determined; hydrodynamic efficiency was not a primary design goal. Using the hydrodynamic parameters borrowed from [16], the glider motion was simulated. In addition, the actual gliding behavior of the GUPPIE was

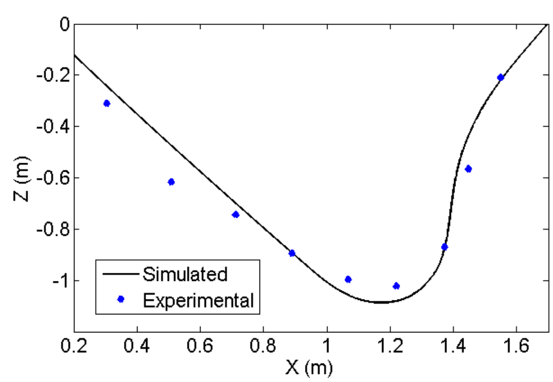

Fig. 3. Simulated and experimental glide paths for GUPPIE.

recorded in a video, and the glide path was estimated using other markings in the video. Figure 3 depicts a comparison between the simulated and actual glider path in one cycle. Note the asymmetry of ascent and descent due to the shifting of the center of the buoyancy mass as water was ejected. The GALUR is expected to exhibit the same behavior, necessitating compensation in the control system.

The GUPPIE is being piloted in an undergraduate curriculum at Michigan Tech, and at the high school level through upcoming summer programs for high school students and summer institutes that train teachers in the GUPPIE curriculum. The GUPPIE design and its educational merits are detailed more fully in [12].

III. Developing and Testing the Littoral Underwater Glider

A. Vehicle conceptual design and component selection

A glider for autonomous littoral underwater research (GALUR) was designed based on lessons learned from developing GUPPIE. The goal of the GALUR design was to produce a glider suitable for both individual and multiple vehicle control system field experiments in under-ice conditions and high-traffic littoral zones. In addition to the high maneuverability and durability required by its primary missions, the GALUR was designed to be low-cost, user-friendly, and easily deployable by one person. Intra-fleet communication was a critical need for a multi-vehicle testbed, requiring an acoustic modem and transceiver in the GALUR. As these vehicles were designed to operate in unpredictable, high-risk environments, some form of obstacle avoidance capability was necessary.

The hydrodynamic design of the GALUR needed to be similar to at least one of the legacy gliders, to allow gained results with this test vehicle to be transferred to a more common vehicle with confidence. The Seaglider was selected because of its excellent hydrodynamic efficiency. This required the GALUR to have rear mounted wings, and a fairly hydrodynamic body. The front endcap was designed as an elliptical ogive shape, to avoid early flow separation. Several shapes of tailcap, stabilizer and wings were tested in SolidWorks Flow Simulation for lift and drag coefficients (see Table II for final values).

A revolved NACA 0051 segment was the most efficient tailcap design tested. Different wing mounting positions were tested. The most efficient mounting point, assuming laminar flow on the hull was maintained past the wings, was centered on the main hull of the glider. However, the wing mounts seemed likely to trigger a turbulent transition and increase drag on the remainder of the hull. The GALUR final design placed the wing on the tailcap; this imposed a 3-5% penalty in lift to drag ratio in laminar simulation, but prevents premature turbulent transition on the hull. The tail cap is also a flooded compartment, which obviates the need for sealing the wing mounts, and increases the reliability of the GALUR. A wing with aspect ratio of 5.6 was selected for the dimensions given in Table III.

The hull design was primarily constrained by manufacturing concerns and sealing. An aluminum 6061-T6 hull was chosen for its high strength and low density. While the GALUR is still designed to be deployable by one student, the size constraints were somewhat relaxed from the GUPPIE. The four-inch diameter GUPPIE hull had limited battery capacity, sensor placement and ease of assembly. The GALUR was designed with a five-inch hull, with a target weight of less than 14 kg. By moving the wings to the back, this still allows one person to easily lift the glider at its center of mass. The GALUR's hull thickness was chosen at 3.18 mm to allow for sealing and threading to mount the endcaps, and to prevent buckling under compressive loads from the endcaps. The length of the straight hull was chosen as 0.67 m, to permit all the subsystems to fit and leave room for non-critical sensor additions.

All the internal components were mounted to a single, half-dovetailed rail, to allow any component to be shifted, removed or replaced without disturbing its neighbors. A rib was added to the bottom to increase stiffness of the rail. A universal mount was designed to lock onto this rail, and provide a locating dowel and two screw holes for mounting additional components. Each internal subsystem used two or three universal mounts to attach to the rail. The rail is then bolted to two rail ends which seat against the inside of the hull. The rear endcap screws into the rear rail end, and the front endcap uses a bolt hole circle to hold the external hull in compression. This allows the rear tailcap to be flooded for internal sensor readings, and easy wing mounting.

The buoyancy engine in the GALUR was based off the same piston-cylinder tank concept used in the GUPPIE. As the pressure requirements were much higher, a pump was used to fill the cylinder instead of direct piston actuation. A custom, piston-actuated cylinder was considered, but was

$$
\begin{array}{ll}
C_L^0 = -0.022 & C_L^\alpha = 0.0431 \\
C_D^0 = 0.205 & C_D^{\alpha^2} = 8 \times 10^{-4} \\
C_T^0 = 0.0843 & C_T^\alpha = -0.0263
\end{array}
$$

TABLE II

First-order Hydrodynamic Characterization (with α given in degrees)

Metric	Value
Dimensions (cm)	12.7 (d) x 81.2 (l)
Wingspan (cm)	60
Total Mass (kg)	10.3
Payload Mass (kg)	2
Endurance (hr)	8
Maximum Depth (m)	20
Minimum Glide Angle (degrees)	25
Displacement (mL)	450

TABLE III

GALUR design characteristics

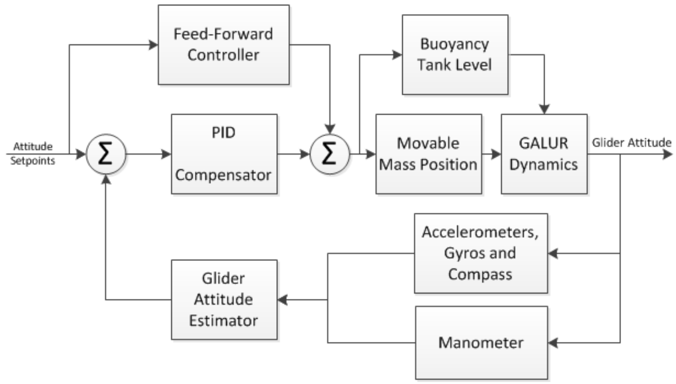

Fig. 4. Initial GALUR Control System

rejected as requiring too much force developed on the piston. The GALUR uses a 12V diaphragm pump for low-flow, high-head efficiency. This is mounted in the front of the glider and draws water in from the front of the endcap. The pump is placed in an H-bridge of solenoid valves, to allow it to pump water either in or out. A flow meter is located at the exit port to indicate the buoyancy mass rate, and allow for feedback control system testing.

The battery pack used in the GALUR was designed for an eight hour endurance, with high control energy usage. The Li-ion battery chemistry was selected for high energy density and low internal resistance. A 14.8V battery pack was selected, as it provides sufficient headroom of regulation over the 12V pump requirement. The estimated average current drain is $<$ 1A during heavy maneuvers. A 13Ah battery pack was selected, yielding an expected endurance of 13 hours. This served as the primary, lateral mass. An optional 5.2Ah battery pack was designed to fit in the controller compartment if no additional control hardware is required for the current test.

The control of the GALUR is provided by moving the center of mass (through shifting the internal battery location) and adjusting the buoyancy system. The GALUR is trimmed to nearly zero vertical CG displacement in the rigid body, with the CG slightly behind the centroid to counter the rear wing location. The longitudinal movable mass is then mounted on a linear guideway, and driven by a DC motor on a rack. Another servo is mounted on that longitudinal moving mass, with its axis of rotation oriented in line with the direction of motion. This has an eccentric mass attached to it, which allows the glider to exhibit roll control. The longitudinal and rotary motors were designed with potentiometers for feedback control. By trimming the glider to near-zero-stability without these eccentric masses, a significant range of roll and pitch will be possible. This system should allow great flexibility in control system implementation, and a limited stability system for high maneuverability. A feedforward/feedback control system will be implemented, and will serve to evaluate the capabilities of this testbed (See Figure 4).

B. Controller and Sensing Design

Currently-available legacy gliders lack the necessary flexibility to meet the needs of disparate applications, and are too expensive for most interested groups to afford loss of a single UG, let alone a fleet of vehicles. The GALUR was designed to serve as a low cost multivehicle control testbed. At 10% of the cost of current UGs, a GALUR fleet is affordable without compromising the sophisticated control components and maneuverability. Moreover, GALUR is flexible in its modular design, making it easy to modify hardware and software, and therefore, serving the purpose of different research groups who need to experiment with and validate control algorithms.

To meet these needs, the GALUR controller needed to have sufficient processing power to run any practical control and sensing architecture. This is actually a very tight constraint, as some optimal control architectures and vision processing can be difficult to implement in real time on a standard PC, and high precision sensor frequency analysis can also require most of the capacity of a typical embedded system. In addition to processing capabilities, the controller needed to be deployable by many different control groups, with varying sensing and control needs. To that end, it should use a widely known hardware interface language, a great deal of flexibility for additional input and output interfaces, and room for sophisticated control algorithms.

Flexibility for both additional input/output interfaces and diverse control algorithms required two different types of controller. Broad processing capability, flexible interface design, and room for high-precision frequency analysis are all best fulfilled using an FPGA-based design. An FPGA provides reconfigurable hardware, so that all processing and algorithms happen at or near the speed of dedicated circuitry. However even simple high-level algorithms tend to take up enormous amounts of space on an FPGA and few control research groups have the ability to write FPGA requirements in a hardware description language (HDL). High-level decisions are much more easily coded on a realtime controller, and most engineers are much more familiar with standard

Controller	NI sb-RIO 9605 -FPGA I/O processing (24k Logic cells, 30k flip-flops, 936kb RAM) -Real-time processor (400MHz, 256MB Flash, 128MB RAM)
Power	One 14.9V 13Ah Li-Ion Battery
AHRS	CHR-UM6 ($\pm$ 2° Pitch/Roll)
Acoustic Modem	SIDMAR AquaCOMM
Motor Controller	Sabertooth 2X5 (5A)
Temperature Sensor	QTI Hydroguard P68

TABLE IV
CONTROLLER SUBSYSTEM COMPONENTS

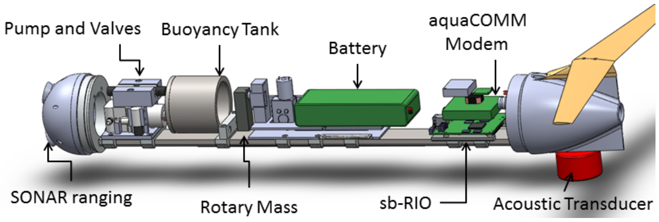

Fig. 5. 3D-model of GALUR.

programming languages.

National Instruments provides a series of controller boards with both an FPGA and realtime processor onboard. These are both programmable using slightly different variations on G, the LabView programming language. While programming an FPGA in G is still somewhat different from traditional processor programming, it is both more straightforward than traditional HDL and can be bypassed transparently if no FPGA capabilities are required for the task at hand. While most of these boards are much larger than the GALUR can accommodate, several low footprint sb-RIOs are available. A National Instruments sb-RIO 9605 was selected, as having all required capabilities and significant additional capacity in processing power, and storage space. The sb-RIO has an integrated 5V RS-232 interface and the FPGA is configurable to produce additional peripherals for any other serial or parallel sensor interface. This combined configurable hardware and traditional processor approach provides maximum sensor and input flexibility for future researchers.

A SANAV FV-M8 GPS module was selected for surface location of the glider. This GPS is inexpensive and uses an integrated ceramic patch antenna for communication. This allowed us to mount the GPS in the evacuated front endcap. When the glider is pitched fully back with the buoyancy mass completely empty, the GPS is raised out of the water allowing it to communicate through the acetal endcap. An AHRS (Attitude Heading Reference System) was needed to track glider location while underwater and out of communication with the GPS system. The UM6 ultra-miniature orientation sensor from CH Robotics was chosen, as it can communicate through a UART with the sb-RIO and was relatively inexpensive. The alignment between the accelerometer axes and the mount is lower precision than those typically used in gliders; this will necessitate more frequent surfacing for the same precision of location.

A camera and associated vision processing hardware would be critical for some inspection and observation missions. An OceanLED underwater camera and a uCFG frame grabber were integrated into an optional RS-232 vision module for the GALUR. A pair of XL-MaxSonar-WRC SONAR sensors are mounted in the front endcap, pointed up and down at the projected angle of attack. This allows one sensor to always be aligned with the direction of motion in steady glides, and the other to be nearly horizontal, permitting both obstacle and environmental measurements.

As the GALUR is intended as a multivehicle testbed, some method of communication was needed between vehicles. A SIDMAR AquaComm acoustic modem was selected for the modulation and amplification of our communication signals, and a cylindrical ceramic transponder was chosen for transmitting the information through the water. Two mounting locations were provided for the transponder: either under the tailcap, or inside it. An exterior mount would significantly increase the drag of the vehicle, while an interior mount would damp the SONAR signal, possibly impairing communication quality and range.

The controller with detailed charateristics summarized in Table IV and these sensor capabilities will allow novel control designs to be tested. Many reservoirs require periodic inspection for early signs of failure [3]; an autonomous glider controller using the SONAR and vision capabilities of the GALUR could be developed for following and inspecting the side of the dam. Autonomous underwater pipeline inspection requires a control system for following a subsea pipeline, which could be implemented using the GALUR's SONAR sensor for mapping. Buoys are frequently deployed near major oil spill zones to track the spread of the contamination, and hang a chain into the water to estimate current and buoy drift. Anti-ship mines are frequently tethered to a subsea anchor by a chain. A fleet of GALURs can easily triangulate a chain's position from the ranges to each of them.

The final design is illustrated in Figure 5 and design characteristics are presented in Table III. The single rail design allows for great clarity of design, modularity, and simple operation. All components can be installed and removed from the same side, and much of the glider volume is free for additional sensors, wire routing, etc. The one-piece hull again simplifies design requirements, allowing a seamless hull, with all efforts toward hydrodynamics focused on the endcaps. The controller area leaves plenty of room for sensor interface circuitry and additional batteries. This design fits its primary goal as a modular, configurable control system testbed, and will facilitate developing new control strategies to increase capabilities in this field.

IV. CONCLUSIONS

This paper describes the design of an inexpensive Glider for Underwater Presentation and Promoting Interest in Engineering (GUPPIE) that served as a control testbed for a Glider for Autonomous Littoral Underwater Research (GALUR) fleet.

In conclusion, disparate task-oriented missions, such as naval submarine tracking, pipeline monitoring and mine detonation require accurate underwater positioning. Many of these applications involve high risk environments, where accidents or enemy action may disable a glider. A fleet of inexpensive underwater gliders with an adaptive control system can serve to mitigate both of these limitations. Intrafleet path-planning and formation deformation can be used to estimate local flow fields, while a robust control architecture allows for mission completion in the event of unit failure. Moreover, at 10% of the cost of current models, the GALUR can serve as a low cost multivehicle control testbed for disparate research groups who need to validate control algorithms.

As a highly maneuverable glider, the GALUR allows researchers to address underwater communication issues by implementing control strategies for individual and multiple vehicle underwater data collection and mapping.

As explained in detail above, the GALUR design is smaller and cheaper than legacy gliders, and is designed specifically for littoral zone maneuvering. The GALUR will be an open source testbed that can accommodate a wide variety of sensors and communication devices - meeting the needs of diverse research groups. LabVIEW provides a straightforward programming interface which can also integrate existing simulation code from MATLAB to allow for easy algorithm implementation. The FPGA will also provide modularity, accommodating a wide variety of sensors. The low price of GALUR makes unit failure relatively insignificant allowing for more aggressive research to be done in volatile environments or with speculative control strategies than is possible with existing platforms.

Future plans include fabrication, hardware testing, vehicle assembly, and basic deployment tests of GALUR. Once a working model is complete and stability bounds have been established, the feedforward/feedback control system in Figure 4 will be implemented and tested in stable motions (steady wings level flight and steady turn). After this, our work will focus on developing and using path-planning algorithms to achieve a more energy efficient path. This process will test different techniques to estimate vehicle position, and different filtering mechanisms to help eliminate sensor bias and noise. Evaluation of maneuverability and ability to perform near shore is also part of future testing at the Lake Superior in collaboration with the Great Lakes Research Center. When the single vehicle system works well, then a fleet of GALUR will be fabricated and multi-vehicle cooperative control algorithms will be implemented. The expected outcome of our research is a sophisticated, maneuverable underwater glider fleet suitable for performing littoral observation and multi-vehicle coordination field experiments.

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