Design of a Low-Cost Open-Source Underwater Glider

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Abstract

Typical buoyancy engine-based Underwater Gliders are highly-complex and cost-prohibitive, generally ranging in price-point from $50,000 to $250,000. A low-cost, Open-Source Underwater Glider (OSUG) was thus developed as a low-cost data-collection and research tool. This glider, OSUG, is a sub-$1000, 1.2m long, 12kg, and capable of 50-hours of continuous operation. Its efficiency, and use-case feasibility were evaluated. The buoyancy engine is constructed of medical grade syringes that pull in water from the environment to simplify the system and lower costs. Direction of locomotion is controlled by altering pitch and roll via changing the center-of-mass. The system was designed to be primarily three-dimensionally (3D) printed and fully-modular to limit cost and ensure reproducibility.

***Index Terms**: open-source, underwater-glider, buoyancy engine, underwater robotics, ocean environment monitoring, mechanical design*

Introduction

Underwater gliders are commonly used in oceanographic research due to their capacity to collect data for long durations and travel long distances[1,2]. Most underwater gliders are based on buoyancy engines, that change their buoyancy relative to the underwater environment by changing their relative buoyancy to sequentially descend and ascend in saw-tooth gliding patterns.

While some low-cost commercial gliders are available[3,4], including the Slocum Electric Glider Coastal made by Teledyne Marine, these gliders still exceed $50,000. Some low-cost academically-focused underwater gliders have been created as well, such as Michigan Tech's Research-Oriented Underwater Glider for Hand-on Investigative Engineering, ROUGHIE, which costs approximately $10,000 in materials to reproduce. Unfortunately, current underwater glider platforms are still reasonably high-cost and do not publish the necessary documentation and files necessary to reproduce them.

OSUG was developed to be the first fully-open source glider as well as the lowest-cost underwater glider ever developed, at less than 2% the cost of commercial underwater gliders. Due to the dramatically-lower cost of OSUG compared to a typical commercial system, numerous OSUG systems can be deployed to collect data from large regions as opposed to localized areas. Further, underwater vehicles always have a risk of becoming lost on a mission, especially when operated untethered[5], or are not recollected due to the high cost of locating and collecting the underwater vehicle[6]. The sub-$1000 price-point of OSUG makes recollection optional.

This paper is organized as follows: Section I discusses OSUG's mechanical architecture; Section II discusses the electronics and control system, and Section III presents plans for the continued development of OSUG.

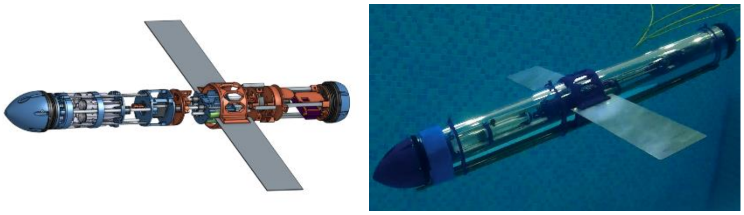

***Fig 1.** OSUG Design and Prototype*

Section I

Mechanical Design of OSUG

OSUG's components are designed to be fully-modular, low-cost, and replaceable. Thus, virtually all of OSUG's components are commercially-available or produced via Fused Deposition Modeling (FDM) 3D printing. In doing so, the barriers-to-entry of creating an underwater glider are considerably lowered.

OSUG was designed in CAD software (Onshape) and is fully variable-driven and parametric, such that a user can easily manipulate numerous variables such as tube diameter, number of syringes in the buoyancy engine, or leading-edge nose taper angle. All parts were also created with a predominantly-flat bottom-surface and few overhangs to eliminate the need for support structures during 3D printing[7]. To also account for the large deviations between different low-cost FDM 3D printers, a set of calibration parts was also created, such that users can print out the calibration parts, measure them using standard metrology equipment (low-cost calipers and micrometers), and input measured values to automatically update the dimensions of OSUG to ensure correct fit between components and subassemblies.

***Fig 2.** OSUG's FDM 3D-Printed Components*

OSUG is comprised of seven subassemblies, including 1.) the hull, 2.) external ballasts, 3.) a buoyancy engine, 4.) hydrofoils 5.) the roll-control subassembly, 6.) the pitch-control subassembly, and 7.) control system. All subsystems are fully-modular to make manufacturing efficient and replacement trivial. All other subassemblies connect to the hull via leading and trailing-edge friction-fit end-caps.

The core of OSUG a hull made of a commercially-available, pressure-resistant 4.5” outer-diameter 4” inner-diameter acrylic tube, into which all modular assemblies are inserted. To seal off the hull from the environment, two commercially-available glider end caps from Blue Robotics[8] were utilized. These end caps are low-cost and designed to have additional subassemblies attached to them.

When fully-assembled, OSUG’s hull is designed to be mostly filled with only air, such that the OSUG has positive buoyancy when submerged in a salt water environment. OSUG has two 3D-printed ballast retaining rings, designed to allow users to add or remove external metal ballasts until OSUG is neutrally buoyant or slightly positively buoyant. Finer adjustments can be made electronically by modifying OSUG’s source code to change the amount of water in the syringes required to achieve neutral buoyancy.

A tapered, 3D-printed nose cone, through which liquid can be taken in and expelled for the buoyancy engine, mounts to the leading-edge cap to seal the front-end of the hull. A commercially-available plate with 3D-printed shroud seals the trailing-end of the hull and enables application-specific sensors to be added. Both end caps also serve to secure OSUG’s major subassemblies. The buoyancy engine is mounted to leading-edge end cap, while the roll-control subassembly, pitch-control subassembly, and control system are mounted to the trailing-edge end-cap.

Typical underwater gliders are based on buoyancy engines using either 1) an oil-transfer system that pumps oil to and from bladders, thus changing buoyancy relative to the environment[3,4], or 2) a thermal buoyancy system that melts a waxy material that has greater volume when melted than when solidified[9], thus also changing the glider’s buoyancy relative to the environment. OSUG uses a less common form of buoyancy engine that modifies buoyancy by drawing in and expelling water directly from the environment. Generally, this is achieved via pumping water into and out of an interior bladder in the glider.

However, OSUG utilizes a piston system to vastly simplify the design. OSUG’s buoyancy engine consists of six 60mL medical syringes, actuated via a NEMA 23 integrated-lead screw stepper. Use of a stepper-driven piston-based system allows the glider to take in and expel precise amounts of water without complicated feedback systems associated with a pump. When the stepper pulls the syringes’ plunger shafts, a vacuum is created, and water is drawn in through the leading-edge nose cone, thus making OSUG denser than the surrounding water, causing descent; when the stepper pushes the syringes’ plunger shafts, the glider expels water, causing it to gain buoyancy and ascend. The buoyancy engine has been cycle-tested to operate effectively to approximately 250 hours, after which the syringes need to be replaced.

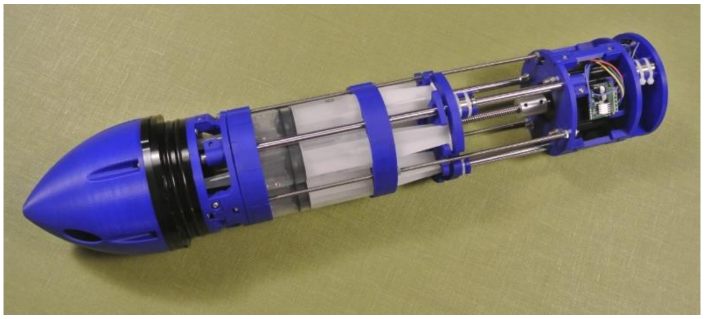

Fig 3. *Buoyancy Engine mounted to Leading-Edge End Cap*

To course-correct against currents and external forces, OSUG is also capable of modifying its center-of-mass by controlling pitch and roll. To do so, OSUG’s batteries are mounted to a pitch-control subassembly. These batteries are actuated axially along the length of OSUG via a lead-screw driven by a NEMA 17 stepper motor to shift OSUG’s center of mass. While the buoyancy engine can be used to adjust the glider’s pitch without a pitch-control subassembly, the addition of a pitch-control subassembly allows a considerably higher glide ratio (less aggressive slope of travel) resulting in longer range and slower speed. Alternatively, a lower glide ratio can be achieved, for more rapid movement at the expense of range[10].

Hydrofoils improve lift of the glider to increase glide ratio. Each hydrofoil is made of 2mm-thick 316-alloy stainless steel plate. A 3D-printed hydrofoil mounting ring holds both hydrofoils approximately horizontal during gliding. A fixed wing design would improve the lift-drag ratio[11] however manufacturing of such a design would reduce reproducibility.

To change roll and thus direction of travel, the entire pitch-control subassembly is mounted to the roll-control subassembly. The roll control subassembly consists primarily of a NEMA 17 stepper motor with an attached planetary gear set. The NEMA 17 motor is held stationary and mounted to the trailing-edge end-cap, while the planetary gear set's output shaft attaches to the rear of and rotates the entire pitch-control subassembly. Thus, OSUG can modify roll by rotating its center-of-mass and therefore turn when gliding.

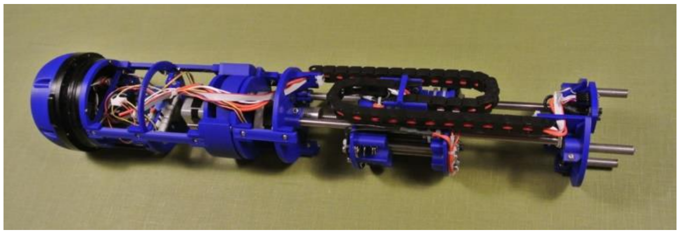

Fig 4. *Pitch-Control, Roll-Control, Control-System Subassemblies mounted to Trailing-Edge End Cap*

The buoyancy engine needs to be attached to the back assembly (consisting of the Pitch-Control, Roll-Control, Control-System Subassemblies), both mechanically and electrically. As the two main assemblies are friction fit into the tubing, there is no lateral force transferred between the assemblies. Three 8mm steel guide pins ensure that the two assemblies retain rotational offset.

Section II

Electrical Design of OSUG

OSUG is controlled by a custom printed circuit board (PCB) using an ATMEGA2560 microcontroller programmed over the Fathom-S communication board using the full-duplex RS-422 protocol. Standard USB is half-duplex, having a timing requirement causing a cable length limitation of 5 meters[12]. The use of the Fathom-S communication board allows for an extended tether length of over 600 meters.

Charging is controlled by a top-side lithium-ion charging circuit, capable of 4A delivery. OSUG power is provided by six energy-dense lithium-ion 18650 cells for a total capacity of 85Wh. Each cell has an ultra-low-power integrated voltage-, current-, and temperature-monitoring circuit for battery protection as determined by the International Electrotechnical Commission (IEC) 62133[13] specification.

Charging and communication is achieved over a IP69K dry mate underwater connector (Bulgin standard series), rated to a 100-meter depth for prolonged periods.

The bottom-side Fathom-S communication board provides 5V supply and serial port communication to OSUG's control board via a 4-pin header. The Fathom-S onboard power regulator provides low-noise 5V supply, with a maximum current of 250mA, to the control board.

Previous designs used the ATMEGA328P microcontroller; testing showed that more sophisticated control was required and that the greater amount of flash memory of a ATMEGA2560 was essential (256kB vs 32kB). A greater number of Universal Asynchronous Receiver-Transmitter (UART) ports allows for the expansion of the sensor array to include Conductivity-Temperature-Depth (CTD) sensors.

The control board uses a triple axis accelerometer and gyroscope (InvenSense MPU-6050 sensor) for an inertial navigation system to accurately determine OSUG's position underwater. The refresh rate was kept low (1.25Hz) and reading acceleration only, in compliance with the datasheet's conditions for low power usage[14].

A high-resolution pressure sensor (MS5837-30BA) was used for depth sensing, as it has an internal oscillator for long-term stability and gel protection with an antimagnetic stainless-steel cap to ensure the module is water resistant. The microcontroller interfaces with the pressure sensor over an I^{2}C bus interface to reliably transition gliding states at specific depths.

Two Allegro A4988 stepper motor drivers are used to drive the pitch and roll stepper motors. These are low current applications, so the stepper motors deliver a maximum current of 1A in these applications. The drivers are connected via 8-pin headers as calibration stresses the driver boards, sometimes requiring replacement.

The control board has an output header for SPI communication protocol, driving an AMIS-30543 stepper motor driver, mounted on the buoyancy engine subassembly. The buoyancy engine stepper motor requires high-torque, so this board provides up to 3A with forced air flow cooling, varied via the SPI interface by the control board from stall detection feedback.

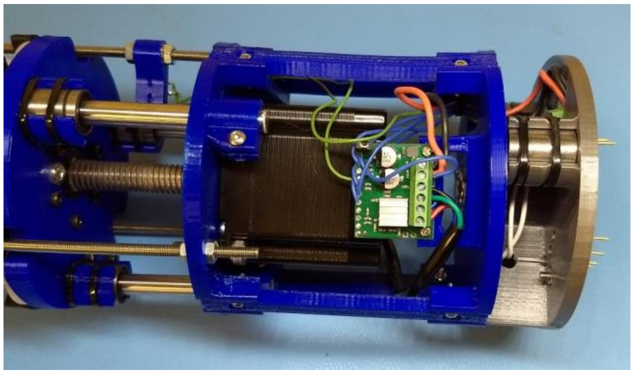

Fig 5. *AMIS-30543 Stepper motor driver mounted adjoining the buoyancy engine NEMA 23*

The control board is also designed such that it can be used as a slave board in conjunction with a Pixhawk 2.1 to control OSUG. In addition to the open-source ArduPilot UAV autopilot, the Pixhawk uses a high-reliability Global Navigation Satellite System (GNSS) for autonomous waypoint navigation.

The board was developed in the circuit board design software, Autodesk EAGLE, as a two-layer board. Trace widths were a default of 16mils for signal traces. The width of traces used for power delivery were calculated using *PCB Toolkit V7.05*, with a copper weight of 1oz and an allowed temperature rise of 15^{o}C. All components were Surface Mount Device (SMD) variants, to reduce surface board-size and cost. Through-hole headers were used for greater structural strength.

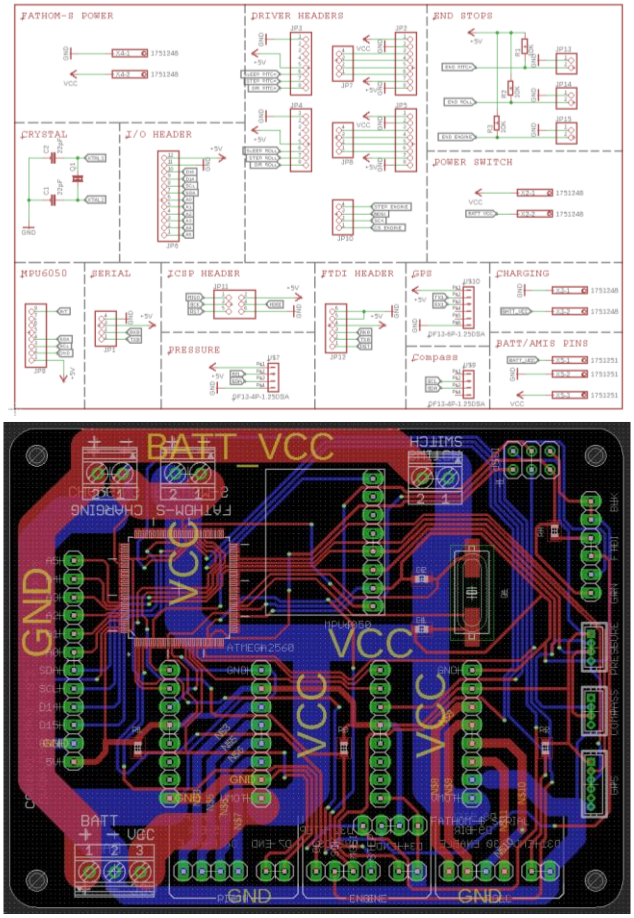

Fig 6. *Schematic and board view of OSUG's control board within EAGLE*

Notably, the assemblies connected to the leading-edge end-cap and the assemblies connected to the trailing-end edge cap must be electronically-connected. To achieve this, there are 14 Harwin 1mm through-PCB connectors, allowing for a current limit of 10A per connector. The terminal pins are 13.2mm high, ensuring a good connection between the two assemblies with a variety of separation distances that arise due to dimension tolerances. Previous versions of this connection system used pogo pins, however these provided a force repelling the two assemblies, reducing reliability. Pogo pins also only have a 3mm pin travel distance, which was insufficient to deal with the variances in distance between assemblies.

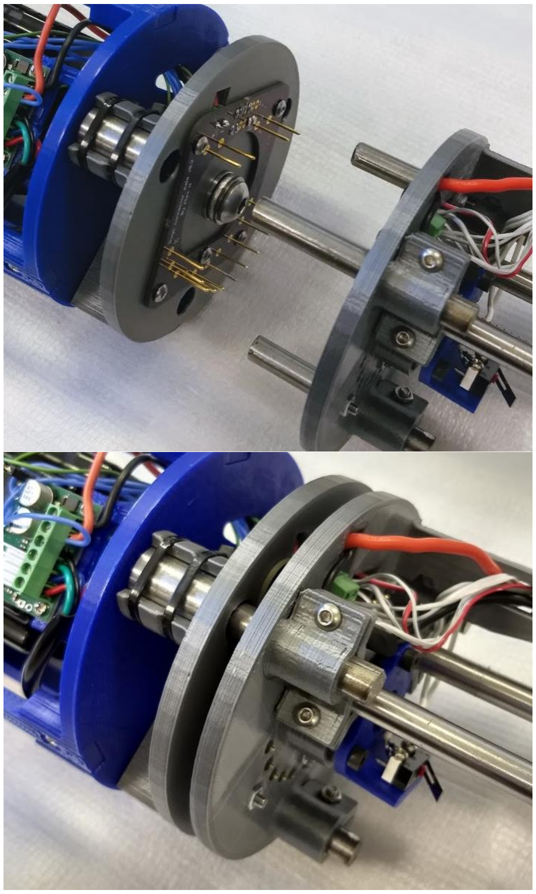

Fig 7. *The buoyancy engine and back subassemblies in unmated and mated positions*

The ATMEGA2560 with Fathom-S communication board allows the control board to be programmed via the Arduino development suite, drawing upon standard libraries for the high-resolution pressure sensor and stepper motor drivers.

Section III

Future developments of OSUG

The mechanical and electrical design of OSUG has been outlined, additional software efforts are still in development – especially with integration with the Pixhawk autopilot suite. While the implementation is possible on current hardware, further software development is required to achieve full autonomy.

In the next version of OSUG, internal mechanisms will be simplified to enable commercialization (while keeping the OSUG open-source), increase reliability and cost optimize. The current buoyancy engine system consists of six 60ml medical syringes which results in limited durability of the buoyancy engine. Currently, a new buoyancy engine with a single custom-built piston is in development.

Currently OSUG can reliably descend and ascend underwater, however future collaborations are to integrate standardized sensor suites. CTD sensors are of importance in underwater data monitoring missions for geophysical or oceanographic research, for instance, to form understandings of species and nutrient distribution or can be used to determine other characteristics of underwater conditions.

OSUG has reduced the high barrier of entry for long distance underwater data collection set by commercial systems. Continued development will enable far more climate science to be conducted by both hobbyist and private research groups. Given the open-source development, as more developers adopt the platform there will be a proliferation of varied capabilities.

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