Mini Underwater Glider (MUG) for Education

By Chunzhao Guo[*], *Member* Naomi Kato[*], *Member*

Key Words: *underwater glider; education; marine systems; low cost; scientific model*

Summary

Mini Underwater Glider (MUG) is an effective and low-cost educational platform for undergraduate student and other inquisitive people in marine systems and underwater robots. Simple but innovative design of MUG could be made by hand tools with ordinary components available in general stores and very low cost. Therefore, it can be used for not only education purposes, but also the markets of toys and scientific models to inspire youth with regards to marine science and engineering. This paper introduces all the aspects of MUG, including design goals, operation principle, mechanical structure, motion analysis, and underwater tests. The experimental results showed a high performance of MUG's glide.

1. INTRODUCTION

An underwater glider is a type of buoyancy-propelled, fixed-wing underwater vehicle without external active propulsion. Relying on the internal actuator to change the position of center of gravity as well as buoyancy, it can convert vertical motion to horizontal with the help of fix-wings, and thereby propel itself forward in a sawtooth path with very low power consumption.

While not as fast as conventional underwater vehicles, underwater gliders represent a significant increase in range and duration compared to vehicles propelled by electric motor-driven propellers, extending ocean sampling missions from hours to week or months, and to thousands of kilometers of range. Besides long range and endurance, the advantages of the underwater glider as a remote sensing platform also include: 1) traveling profile samples horizontally and vertically; 2) regular surfacing for GPS navigation and two-way communications; 3) quiet with minimal impact in the environment being sensed 1). Therefore, more and more researchers are focusing on this topic, and many underwater gliders have been developed. Some of them even can be purchased in markets nowadays.

Actually, the concept of the underwater gliders was proposed initially by Henry Stommel in 1989 2), and it has taken some time to bring the concepts to reality. As part of the US Navy Office of Naval Research (ONR) sponsored Autonomous Ocean Sensing Network (AOSN) program, three oceangoing gliders have been developed since 1995, including the SLOCUM glider 3), the Spray glider 4) and the Seaglider 5). These gliders are designed with similar functional objectives for long-duration, ocean sensing missions, so they are similar in size, weight and configuration, each measuring approximately 2 meters in length and weighing around 50kg. Each has a cylindrical hull, two fixed wings and a tail 6). As of 2006, the ONR is developing the world's largest glider, the Liberdade/XRay, which uses a blended wing body hullform to achieve hydrodynamic efficiency and space for energy storage and payload 7). In Japan, an underwater glider with independently controllable main wings was developed by M. Arima et al. of Osaka Prefecture University 8). Kawaguchi et al. 9) of the University of Tokyo and Yamaguchi et al. 10) of Kyushu University have also developed glider-type underwater vehicles. Meanwhile in China, a shape optimized underwater glider has been developed by Shenyang Institute of Automation, Chinese Academy of Sciences 11).

As a matter of fact, besides the uses for industrial application and oceanographic measurement, underwater gliders can also be used for education purposes. The junior students registered in the Division of Global Architecture, School of Engineering, Osaka University should take the course of Marine Systems Engineering in their 2nd semester. The main goals the course pursues are: to teach students about the knowledge of marine systems engineering; and more important, to train them how to integrate knowledge they gained before as well as team work to solve a real problem.

The Mini Underwater Glider (MUG) presented in this paper was developed in order to use it for the class and show the students how an underwater glider works, as well as provide a creative platform for marine systems engineering. Thus, it is quite different from the underwater gliders described before, due to the

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[*] Osaka University, Graduate School of Engineering, Department of Naval Architecture and Ocean Engineering

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different design goals as well as constrains: to use limited budget and ordinary components available in general stores to build a simple while effective underwater glider that can simultaneously change the position of center of gravity as well as buoyancy automatically and periodically, and swim forward in a sawtooth path in an aquarium. Therefore, compared to the parameters such as cruising velocity, operation depth, maneuverability, etc., the size, weight and cost are more important.

It should be noted that the purpose of this research is not to bring forth groundbreaking developments in technology. Our development work focused on building an effective while low-cost platform in marine systems and underwater robots, which is affordable for medium- to small-sized educational and research centers and groups, not only to big institutions. Therefore, it can help getting more people, especially young students and kids, interested in the field of marine systems and underwater robots, which should be one of the most important objectives of our research.

2. GLIDER OPERATION

The underwater glider is neutrally buoyant. It moves with the net buoyancy changed from negative to positive in a cyclic fashion by using a displacement piston pump or a pressure-resistant balloon with oil inside to move water into and out of the ballast tank, or controlling vent valve of ballast tank and blow valve of compressed air tank, just like naval submarines. Meanwhile, an internal mass can be redistributed to change the position of the glider’s center of gravity, which results in a periodic change of the pitch angle of the glider. The vertical motion due to these changes in net buoyancy as well as pitch angle is converted into horizontal motion through the wings fixed on both sides of the glider. Thus, the underwater glider can move forward without external active propellers.

The movement of the underwater glider in a sawtooth trajectory is illustrated in Fig. 1, where G, F, L, D and V represent gravity, buoyancy, lift, drag and the moving direction, respectively. The process of the diving and surfacing in one cycle is:

1) To dive, the piston begins to pump water into the ballast tank. And the internal mass is moved forward to make the glider stoop.
2) The glider descends due to the negative net buoyancy, and upward lift is generated by the fixed wings and body, whose horizontal component force helps the glider move forward.
3) To ascend, the piston begins to push water out of the ballast tank, making the glider buoyant. And the internal mass is moved backward to help the body nose up.
4) The glider ascends due to the positive net buoyancy, and the horizontal component force of the downward lift helps the glider move forward.
5) The glider returns to the original depth and prepare for the next diving.

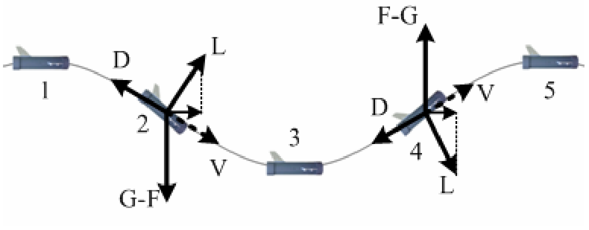


Fig. 1 The sawtooth trajectory and force analysis of glide motion.

3. DESCRIPTION of MUG

3.1 Configuration and Specifications

The MUG consists of a cylindrical hull with fixed horizontal and vertical wings, as shown in Fig. 2. These wings provide gliding lift as well as stability.

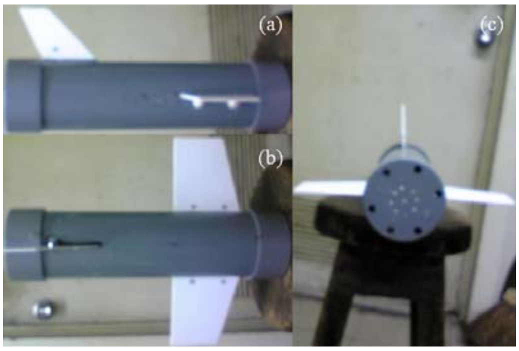


Fig. 2 Side (a), top (b) and front (c) views of the MUG.

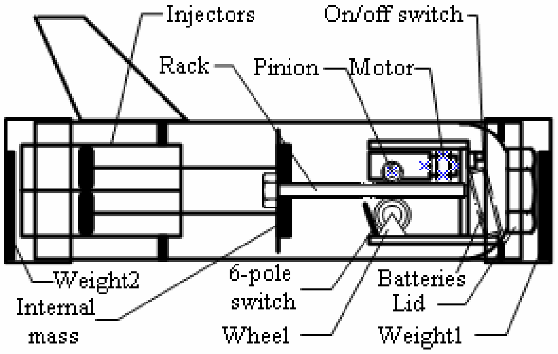
Measures and dimensions of the MUG are shown in Tab. 1, from which we can see that the weight is light, the size is small, and the cost is low.

Tab. 1 Specifications of MUG

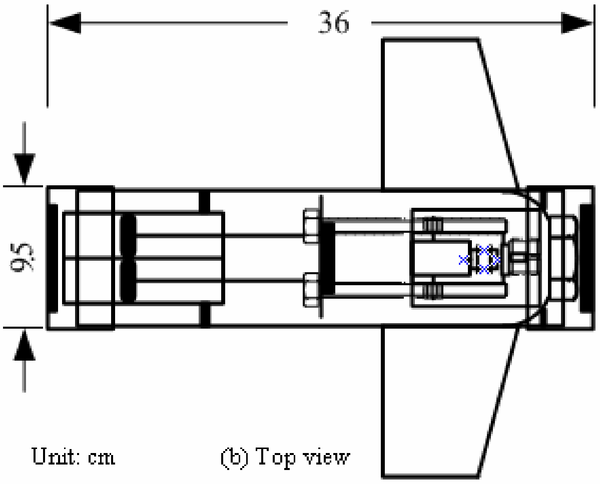
Weight (g)	1920
Hull length (cm)	36
Hull diameter (cm)	9.5
Wing span (cm)	10
Vertical stabilizer length (cm)	7
Buoyancy change (g)	±26.5
Maximum pitch angle change (º)	48.58
Batteries	1.5V x2
Costs (U.S. dollar)	35

3.2 Mechanical Structure

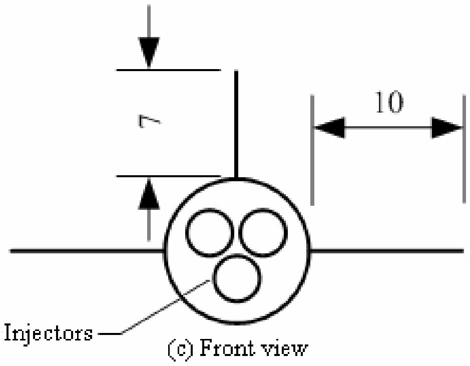
The layout of MUG is shown in Fig. 3. The nose of the cylindrical hull is covered by a removable lid for the convenience of turning on/off the MUG as well as changing batteries. Three 60ml injectors are fixed together and installed aft inside the cylindrical hull. A 120g palladium weight, which works as the internal mass to change the position of center of gravity, is bound with the pistons of the injectors.



(a) Side view



(b) Top view



(c) Front view

Fig. 3 Schematic of MUG

A RF-280 direct current motor, with the specifications shown in Tab. 2, is used as the actuator to drive the pistons and internal mass through a gear box with the gear ratio of 344.2:1 to reduce the rotary speed.

Tab. 2 Specifications of the RF-280 motor

Normal Voltage	3.0V
Normal Load	1.47mN*m (15.0g*cm)
Speed at No load	8,800rpm
Speed at Normal Load	6,600rpm
Current	650mA

A rack-and-pinion is employed to transmit the output torque of the gear box's shaft to the pistons and drive them in a linear motion. A 6-pole mechanical power switch is connected with the rack by a steel wire to change the direction of motor's voltage input so that the rotary direction will be changed according to the position of the pistons and internal mass. The electric circuit is shown in Fig. 4.

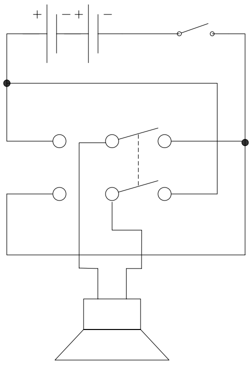


Fig. 4 Electric circuit of MUG

At first, the rotation of the motor drives the rack together with the internal mass and pistons moving to the nose of the glider. The buoyancy will decrease due to the water pumped into the injectors. So is the pitch angle due to the center of gravity moving forward. When the rack reaches the position where the 6-pole switch is just pulled to the other side by the steel wire connected between them, the motor's rotary direction will be changed. Subsequently, the rack together with the internal mass and pistons will begin to be moved backward, which makes the buoyancy as well as pitch angle increase. When the rack reaches the other position where the switch is pulled again, the motor's rotary direction will be shifted to drive the rack together with the internal mass and pistons moving forward again. In this way, MUG is capable of changing its buoyancy as well as pitch angle automatically and periodically, which is the essential condition for the sawtooth trajectory of glide motion. The moving range of the internal mass and pistons is determined by the length of the steel wire.

The mechanical structure of MUG was designed as described above in order that all the components could be bought in general store for the sake of simplicity and low cost. And most of these components can then be re-used in the successive course of next year.

3.3 Motion Analysis

The MUG's hull is symmetrical with wings and tail attached. So we assign the body-fixed coordinate frame on the vehicle body as shown in Fig. 5. Let o lie in the middle between the center of buoyancy and the center of gravity, let ox lie along the long axis of the vehicle (positive in the direction of the nose of the glider), let oy lie in the plane of the wings and oz in the direction orthogonal to the wings. (O, X, Y, Z) is the earth-fixed coordinate frame.

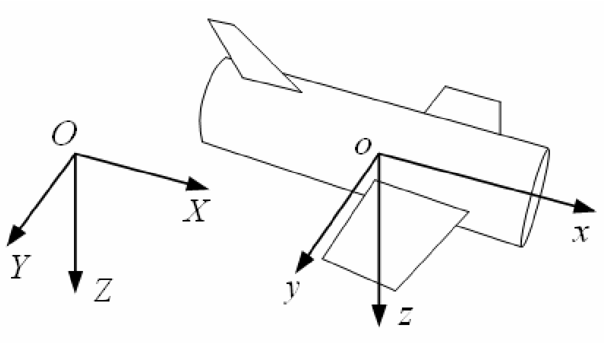


Fig. 5 Coordinate frames of the glider's motion

The majority of the operational time of a real glider is spent at steady glides. The transitions and inflections between steady glide equilibria are relatively slow and gradual. And the hydrodynamics of the flow about the glider are much more complex when it experiences high accelerations or angular rates. More discussions are available in 6) and 12). Here, we only analyze the glide motion in equilibrium state. In this case, the glider is specialized to the longitudinal plane of (X, O, Z).

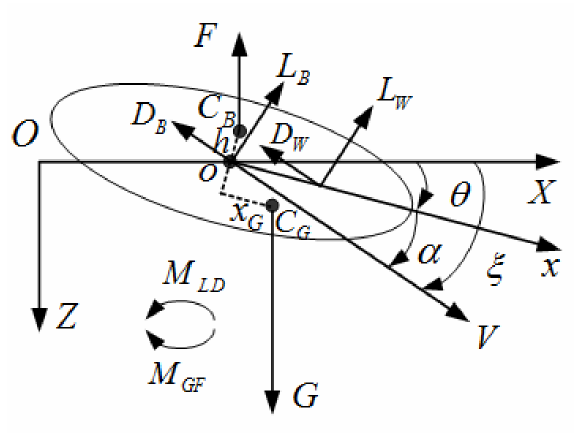


Fig. 6 Diving motion of the glider

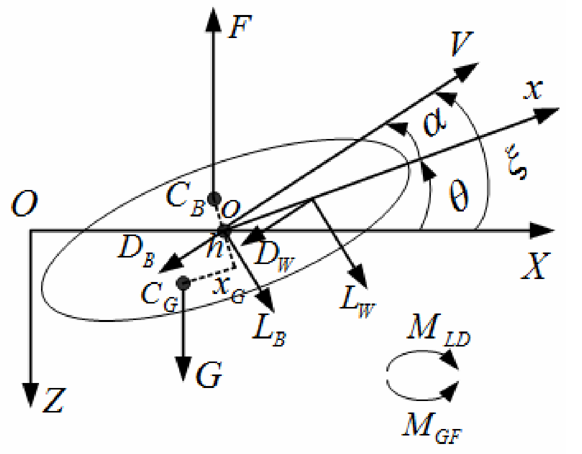


Fig. 7 Surfacing motion of the glider

Figs. 6-7 show the diving and surfacing motions of the glider. The forces as well as the moments must be balanced due to the equilibrium state. Thus, the following equations must be satisfied.

$$\begin{cases} L\sin\alpha - D\cos\alpha + |F-G|\sin\theta = 0 & (1) \\ L\cos\alpha + D\sin\alpha - |F-G|\cos\theta = 0 & (2) \\ M_{LD} = -M_{GF} = G(x_G\cos\theta - \frac{1}{2}h\sin\theta) - \frac{1}{2}Fh\sin\theta & (3) \\ \theta + \alpha = \xi & (4) \\ \xi = -\tan^{-1}(\frac{D}{L}) & (5) \\ D = \frac{1}{2}\rho C_D(\alpha)AV^2 \approx (K_{D0} + K_D\alpha^2)V^2 & (6) \\ L = \frac{1}{2}\rho C_L(\alpha)AV^2 \approx K_L\alpha V^2 & (7) \end{cases}$$

where, F, G, L_w, D_w, L_B, D_B are buoyancy, gravity, lift and drag by wings as well as lift and drag by body, respectively. θ is pitch angle, α is the angle of attack, ξ is the glide path angle. x_G, h are the transverse and longitudinal displacements between the center of buoyancy and the center of gravity in the body-fixed coordinate, respectively. M_{GB}, M_{LD} are the moments acting on the origin o produced by gravity-buoyancy forces and drag-lift forces, respectively. C_D, C_L are the standard aerodynamic drag, lift coefficients by cross sectional area, A is the maximum glider cross sectional area, and ρ is the fluid density. K_{D0}, K_D, K_L are constant coefficients which can be obtained by the experiment 6) 12). Eqs. (1)-(2) are obtained from the balance of force in the axis of ox and oz. Eq. (3) is derived from the balance of moments. Eqs. (4)-(5) show the relations between the pitch angle, angle of attack and the glide path direction. And Eqs. (6)-(7) show the drag and lift forces are proportional to the quadratic and linear polynomial of angle of attack, respectively.

3.4 Experimental Results

An underwater gliding test was conducted in an aquarium with the dimension of 180cm × 60cm × 60cm. Let the origin O of the earth-fixed coordinate frame coincide with the upper left vertex of the aquarium. The transversal displacement, the depth of the origin o of the body-fixed coordinate frame as well as the pitch angle of the MUG's sawtooth glide are shown in Fig. 8.

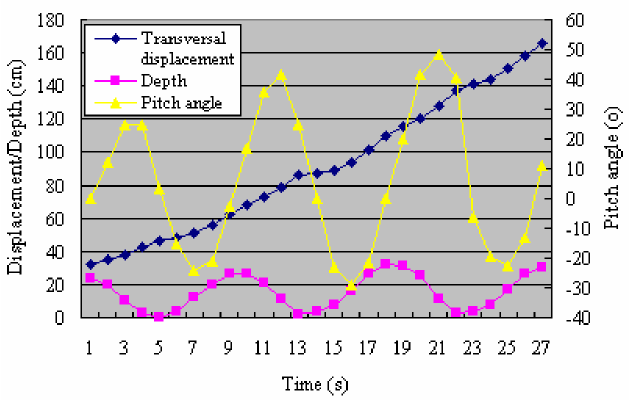


Fig. 8 MUG data from gliding test

From Fig. 8, we can see that the MUG experienced three diving and surfacing cycles, and the period of one cycle is 9.0 s. The depth range of the motion is mainly between 0 cm and 32.1 cm. The average forward velocity is 5.13 cm/s. Besides, the image sequences of the second cycle are given in Fig. 9. Both figures prove that the best velocity performances are during diving and surfacing, and the transitions and inflections between them are relatively slow and gradual.

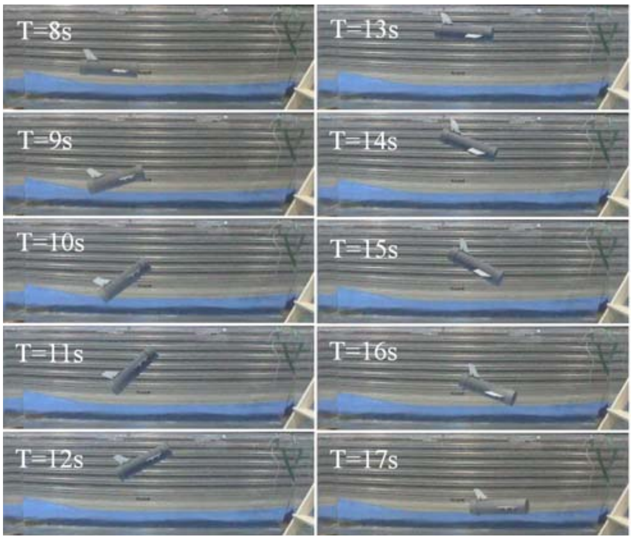


Fig. 9 Image sequences of one cycle

As we can see, the experimental results showed a high performance of MUG's glide, which proved the effectiveness of the low-cost robot MUG.

4. CONCLUSION

The MUG was designed, manufactured and tested for an undergraduate course of Marine Systems Engineering to show students the working principle of underwater gliders, and provide a creative platform for marine systems exploration. Thirty students were divided into 8 groups. And each group was encouraged to propose new ideas in building their own glider on the basis of MUG, without using any kit. In the process, several important and encouraging features of the student's work were observed:

1) Most of the student groups succeeded to arrive at original and creative solutions to their design. The reasons for the group that couldn't finish mainly include the complicated design and limited period of time.
2) Design solutions were achieved through invention, experimentation and discussion and not through didactic, prescribed instructions.
3) The iterative engineering design was highly apparent in each group's work, with solutions evolving through successive cycles of designing, testing and modification. Students were easy to feel frustrated when they encountered some problems in the first time. And then they took pride in solving those problems. Gradually, they became more patient and persevering, which are the essential characters for a researcher.
4) Positive teamwork habits were induced within each group during the discussion, allotment and collaboration in the work.
5) Students were highly engaged in the work, and enjoyed what they were doing.

More details and information of the students' work can be viewed on the project web site: http://www.naoe.eng.osaka-u.ac.jp/naoe/naoe7/MUG.html. These innovative designs of MUG's mechanical structure enabled a simple, low-cost while effective underwater glider. Thereby, besides the use for education, MUG also has the potential for the markets of toys and scientific models so as to inspire more youth with regards to marine science and engineering.

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