

# A High Accuracy Attitude System for a Tailless Underwater Glider

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**Abstract** — The Guidance and Control system is a critical part of the design of a drone. This paper explains the study of a high accuracy attitude system for the SQUID TUG, a Tailless Underwater Glider drone. As the vehicle does not have movable surfaces, the entire manoeuvring system is geared to the buoyancy system and the centre of gravity displacement. We will examine the control system for a tailless AUV (Autonomous Underwater Vehicle) without any movable control surfaces embedded in the hydrodynamic flow whose actuators may require "waterways" through the hull.

**Keywords** — Accuracy, Attitude, SQUID, TUG, Tailless, Underwater, Glider, AUV.

## I. INTRODUCTION

The instrumental exploration of the underwater world often requires that high depths data should be collected over a continuous period of time that can go from a few weeks to several months. For this reason, normal AUVs are unsuitable because of their too short endurance; the ROVs (Remotely Operated underwater Vehicle) do not allow a high operative range and therefore require the constant presence of a supporting ship.

One of the first solutions adopted was ALACE, a drift buoy that could suitably adjust its operational depth: once it reached the surface, it transmitted the data collected to the Argos satellite system [1].

The need to get rid of the randomness of the currents, and an ever-expanding miniaturization of electronic components, have led to the natural development of the underwater gliders.

An underwater glider is an Autonomous Underwater Vehicle (AUV) that, changing its buoyancy, moves up and down in the ocean like a profiling float [2]. Unlike a float, an underwater glider uses hydrodynamic wings to convert the vertical motion to horizontal, moving forward with very low power consumption. Fig. 1 shows the example of our AUV called SQUID.

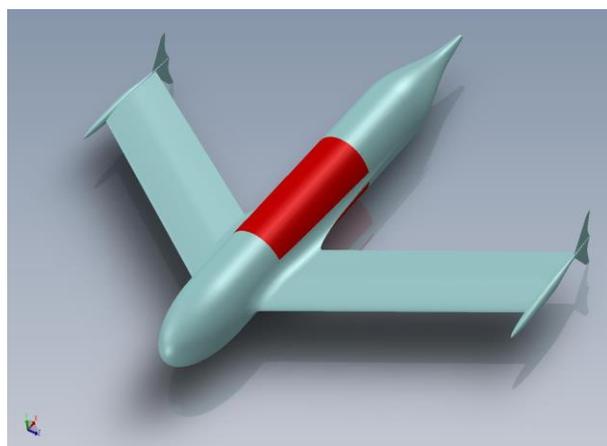


Fig. 1. SQUID TUG (Tailless Underwater Glider) prospective view.

While not as fast as conventional AUVs, gliders using buoyancy-based propulsion increase the range and the endurance compared to motor-driven vehicles, may extend the mission to months, and to several thousands of kilometres of range [4].

An underwater glider follows an up-and-down, sawtooth-like profile through the sea, providing data on temporal and spatial scales unavailable to previous types of AUVs [6], 7, 8, [9].

## II. SQUID'S ARCHITECTURE



Fig. 2. Fuselage section (cutaway).

As Fig. 2 shows, the SQUID is a tailless sub glider: the

cylindrical fuselage (hull) has a constant section (22 mm external diameter approx.), with an elliptical dome on the nose and a hydrodynamic fairing in the tail.

The fuselage (hull) is made out of Aluminium 6061-T6: it has excellent joining characteristics, good acceptance of applied coatings and combines relatively high strength, good workability and high resistance to corrosion.

The wings are made of Ultem 1000 (Polyetherimide high density polymer) has a high dielectric strength, inherent flame resistance and extremely low smoke generation; furthermore, it has high mechanical properties and performs in continuous use to 170 °C.

The vehicle has no movable control surfaces embedded in the hydrodynamic flow whose actuators may require possible "waterways" through the hull.

#### A. Fuselage

The fuselage is composed by five coaxial cylindrical compartments (or bays):

- **Payload Bay:** the nose cone has an elliptical shape (prolate hemispheroid) and contains the (customizable) payload and the ancillary systems, e.g. based on the new Raspberry system [10], [11], [12][13], [14]. The front section (up to the first bulkhead) is all an empty space that can be filled with all the instrumentation needed up to a diameter of 400 mm. This peculiar radome allows accommodating any type of electromechanical sensor. If an active sonar is required, an appropriate version of the radome is available. The second part of the bay accommodates all the ancillary services such as payload power packs, thermal control, and other instrumentation recording and storage devices
- **Navigation and communications bay:** contains the Glider Integrated Control System (GICS), the INS (Inertial Navigation System) platform and the radio communication systems (Global Positioning System-GPS, Iridium RTx and HF emergency beacon). The GICS oversees all the functions of navigation, guidance and vehicle control. In the run-up phase, the AUV receives its position via Global Navigation Satellite System-GNSS (which cannot be done if immersed), and connects itself to the Iridium communication satellite system, provides its own position to the user and downloads the navigation or payload. Then if necessary, get new program parts and run them. In case of recovery from the support ship there is a beacon in HF band to facilitate the homing.
- **Battery bay:** contains the battery pack and the servomotors to trim and regulate pitch and heading (yaw) of the AUV. The batteries are mounted on a special support (cradle) and actuated by servomotors (controlled by the OBC) that allow the forward/backward scrolling (for pitch control) but also the right/left tilt for intrinsic direction control (see Fig. 3).

- **Buoyancy Control Bay:** it contains the buoyancy motor and the oil tank. It provides to balance the system longitudinally by adjusting the level in the reservoir. The bay also supports bulkhead load. The buoyancy motor has the task of pumping oil into the bladder and, in the event of a serious emergency, if ordered by the OBC, it can swell the bladder to the maximum in order to reach rapidly the surface.

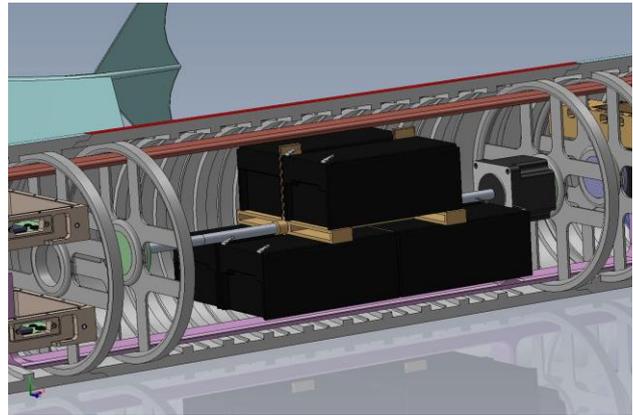


Fig. 3. Cutaway of Pitch-Heading control system (mock up arrangement).

- **Hydrodynamic fairing:** it contains the oil bladder. It is open to the water and provides a slender shape to the AUV. The fairing has the task of not disturbing the hydrodynamic flow of the fuselage and closing the fuselage in closure. In any case, it can withstand considerable loads: for this reason, there are several reinforcements. It also protects the bladder from the flow and its dynamic loads, which could deform it.

#### B. Wing

The wing has a high aspect ratio with no dihedral and a swept of  $\Lambda = 30^\circ$ : his thickness is constant.

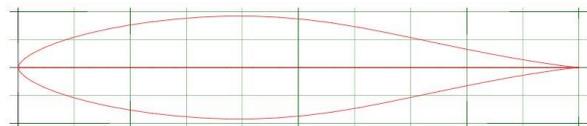


Fig. 4. The Eppler E838 Hydrofoil aerofoil.

The aerofoil is symmetric, type *Eppler E838 Hydrofoil* aerofoil (see Fig. 4): it was intended for use at high Reynolds' numbers; the foil is optimized for use as a hydrofoil wing and at low speeds of the AUV expresses its best lift/drag rate. The choice of such a thick profile is due to two factors: first, the wing is subjected to considerable loads due to the aspect ratio despite the speed remains modest. The second is that in such a thick section it is possible to accommodate a hollow tubular aluminium spar, which increases flexural rigidity.

Each wing tip is provided with a *Küchemann carrot* [15] and a symmetric winglet [16] in order to increase lateral

stability and to reduce drag by partial recovery of the tip vortex energy. A *Karman* aerodynamic fitting connects the wing to the fuselage [17].

### III. CONTROL SYSTEM

The drone control system is extremely simple [18]: to vary the buoyancy of the vehicle, is sufficient that the buoyancy motor pumps the oil into the bladder: so the overall volume increases and the drone begins to float. In order to dive the glider, it is necessary to reduce the amount of oil in the bladder [19].

For the pitch setting, is necessary to move the battery pack (and therefore the centre of gravity  $C_G$ ) forward or backward [20]. However, in order to control the heading, [21] it is necessary to tilt the pack at a certain angle [22].

#### C. Buoyancy System

In order to reduce the force required to actuate the oil piston, which pushes the oil in the bladder at high depth, is necessary to reduce the piston surface (diameter) and increase the stroke. So, the buoyancy engine resembles to a “shotgun” [23].

The evaluation of the buoyancy  $B$  of the drone is made considering the buoyancy of the naked glider [24] (as a rigid body) and the variable component due to the bladder and the buoyancy motor [25]. So, the total buoyancy force (see Fig.5) on the glider is:

$$W_{TOT} = W_{DW} - B_{GB} - B_{BB}$$

where:

$W_{TOT}$  = Net total “weight” in the water

$W_{DW}$  = Dry Weight of the glider

$B_{BB}$  = Buoyancy of the oil bladder.

$B_{GB}$  = Buoyancy of the naked glider.

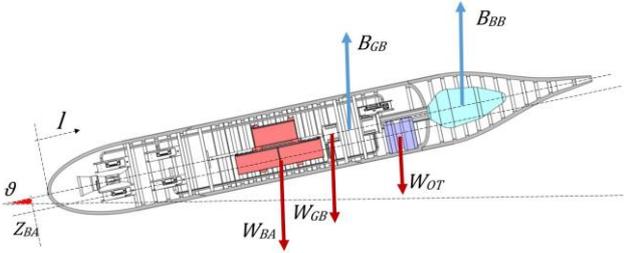


Fig. 5. Pitch balance.

#### A. Pitch Control System

We now consider the attitude of the drone with a pitch angle  $\vartheta$  (see section)

For the balance of the forces on the Z axis we have:

$$\sum F_z = W_{BP} + W_{OT} + W_{GB} + B_{GB} + B_{BB} = 0$$

where:

$W_{BP}$  = weight of the battery pack.

$W_{OT}$  = weight of the oil tank.

$W_{GB}$  = weight of the naked glider.

At the equilibrium we have:

$$\sum M_Y = (l_{BA} + z_{BA} \tan \theta) W_{BA} + l_{OT} W_{OT} + l_{GB} W_{GB} - l_{GB} B_{GB} - l_{BB} B_{BB} = 0$$

For the position of the Centre of Buoyancy  $C^B$  and the Centre of Gravity  $C^G$  we have:  
the Centre of Gravity on the X axis is defined as:

$$C_X^G = \frac{l_{BA} W_{BA} + l_{OT} W_{OT} + l_{GB} W_{GB}}{W_{BA} + W_{OT} + W_{GB}}$$

the Centre of Gravity on the Z axis is defined as:

$$C_Z^G = \frac{z_{BA} W_{BA}}{W_{BA} + W_{OT} + W_{GB}}$$

the Centre of Buoyancy on the X axis is defined as:

$$C_X^B = \frac{l_{GB} B_{GB} + l_{BB} B_{BB}}{B_{GB} + B_{BB}}$$

the Centre of Buoyancy on the Z axis, (by definition):

$$C_Z^B = 0$$

#### D. Heading Control System

To obtain a variation of the heading of the vehicle, due to the absence of the tail, rudder or ailerons, is necessary to move the centre of gravity around of the X axis [26][27].

At the equilibrium, for the roll  $\varphi$  angle we have for the roll forces balance (see Fig.6):

$$\varphi = \frac{z_{BA} \cos \alpha W_{BA}}{Z_{GB} (W_{GB} + W_{OT}) + Z_{BA} W_{BA}}$$

In static conditions, if we move the  $W_{BA}$ , the only effect is the increase of the  $\varphi$  angle [28].

When the AUV is “gliding” (i.e.: diving in constant speed) the effect is totally different: the up-going wing increases the local angle of attack  $\alpha_{ATT}$  so the lift and the drag increases while the down-going wing reduces the angle of attack, the lift and the drag, producing a rolling (also called 'banking' [29]) moment about the aircraft's longitudinal axis.

In our case, the nose of the drone rotates to the up-going wing [30].

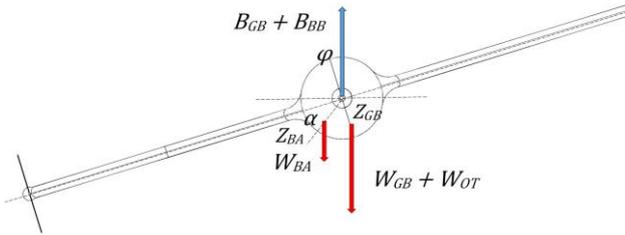


Fig. 6. Roll forces balance.

In particular, the roll motion is characterized by an absence of natural stability; in fact, there are no stability derivatives that generate moments in response to the inertial roll angle [31] (see Fig.7).

A roll disturbance induces a roll rate, which is only cancelled by water viscosity: this takes place with insignificant changes in some sideslip and a yaw rate [32].

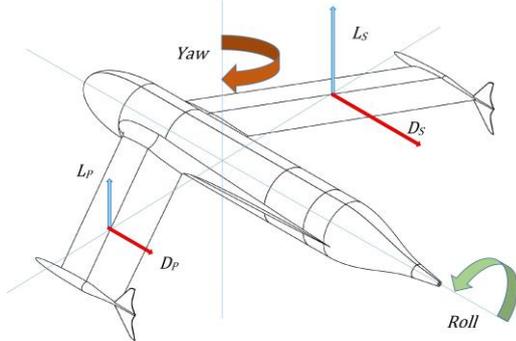


Fig. 7. Banking effect.

#### IV. DYNAMIC VERTICAL FORCES BALANCE

In this section, we consider the drone diving (or emerging), at constant speed (see Fig. 8) [33].

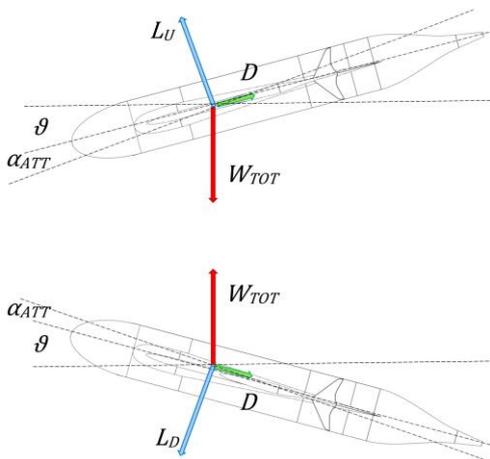


Fig. 8. Dynamic vertical forces balance (immersion and emersion phases).

At the equilibrium, the dynamic on the vertical plane is, at constant speed:

$$\overline{W_{TOT}} + \vec{L} + \vec{D} = 0$$

The expression for the Lift is:

$$L = \frac{1}{2} \rho v^2 S C_L$$

According to the E838 characteristic “Cl vs. Alpha” (see Fig. 9) when the angle of attack  $\alpha_{ATT} = 0^\circ$  (is null) the  $C_L$  is zero so the lift force L is null [35].

This shows that the drone cannot progress horizontally at constant speed (straight and level): the only mission profile allowed is a sawtooth curve [36].

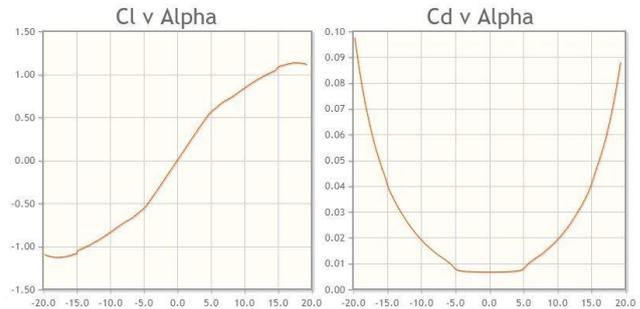


Fig. 9. Eppler E838 Hydrofoil characteristics (Re=106).

#### V. CONCLUSIONS

From the analysis made, it is clear that it is not possible to separate the buoyancy control system from the attitude control system as the motion equation directly affects the lift force and hence on the pitch. In addition, the speed during the banking is directly proportional to the lateral displacement angle of the Centre of Gravity and the rate of descent.

Given the above, w.r.t. previous similar systems, our shows the following novelties:

- the attitude system control is optimized for a Tailless Underwater Glider with a non-negligible wingspan: the wide wing surface allows a smooth glide slope and an excellent operational range;
- the AUV has no movable control surfaces in the hydrodynamic flow: so the actuation of the attitude is based only on the variation of buoyancy and the displacement of the centre of gravity.

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