Switching control of an underwater glider with independently controllable wings

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Abstract: This paper presents a control-oriented dynamic model of an underwater glider with independently controllable wings. We show that this particular feature is particularly useful to improve the vehicle’s maneuverability.

1. INTRODUCTION

Underwater gliders are winged Autonomous Underwater Vehicles (AUVs) that, unlike thrusters’ propelled vehicles, can be employed for long-term and flexible missions, such as oceanographic sampling and underwater surveillance. The underwater glider concept (Stommel [1989]) motivated the development of several prototypes, for instance the “Slocum” (Webb et al. [2001]), the “Spray” (Sherman et al. [2001]) and the “Seaglider” (Eriksen et al. [2001]). These are all buoyancy-propelled, fixed-winged gliders which shift internal ballast to control the attitude, see (Leonard and Graver [2001]).

As underwater glider can be operated in high-efficiency conditions of reliance on the battery power, an accurate control system is crucial for their performance and, especially, endurance. Most importantly, the use of feedback control can provide robustness to uncertainty and disturbances (Leonard and Graver [2001]). Among others, we refer the interested reader to (Bhatta and Leonard [2004]), (Mahmoudian and Woolsey [2008]), where some state-feedback control schemes are proposed for underwater gliders having fixed hydrodynamic wings.

More recently, the need for higher maneuverability motivated the development of underwater gliders with movable rudder (Noh et al. [2011]) or even with independently controllable wings (Arima et al. [2009]). For instance, in (Arima et al. [2009]) many experimental tests are performed with the “Alex” glider to also characterize the so called “lateral response”. This latter characteristic is clearly not available if the glider is just equipped with fixed hydrodynamic wings.

In this paper, we consider the concept of the underwater wave glider (Caiti et al. [2012]), capable of both wave-propelled surface navigation and buoyancy-driven underwater motions, in its operation mode of underwater glider. As a consequence, the hydrodynamic wings of the vehicle are positioned in the back of the main hull. In particular, we propose a state-feedback switching control scheme for the three-dimensional path-following task (Encarnação and Pascoal [2000]), (Aguiar and Pascoal [2002]).

The paper is organized as follows. Section 2 contains the modeling of the vehicle and the characterization of the actuators, namely the ballast and the independently controlled wings. Section 3 presents a switching control scheme for a path-following maneuver. Some simulations are commented in Section 4. In the last section we conclude the paper and outline some future lines of research.

2. UNDERWATER GLIDER MODEL

In this section we present the modeling of the underwater glider, with particular attention to the functional characteristics of the control actuators. The vehicle has got a time-dependent mass \( m(t) \) and a Center of Gravity (CoG) with variable position \( r_g(t) \) due to a ballast tank, positioned on top of the vehicle’s hull.

For any generic vector \( v \), let us adopt the notation with superscript \( b \) to indicate the components of \( v \) expressed in the body-fixed frame “attached” to the vehicle; while we use the superscript \( n \) to indicate the navigation reference frame. The equations governing the dynamics of the position and of the velocity of the CoG are

\[
\dot{r}^b_g(t) = \frac{\Lambda + \dot{Y}(t)}{m(t)}, \quad \dot{v}^b_g(t) = \frac{\dot{Y}(t)}{m(t)} - \frac{\dot{m}(t)}{m(t)} \dot{r}^b_g(t), \quad (1)
\]
where $\Lambda$ and $\Upsilon(t)$ are, respectively, the static and the dynamic contributes of the CoG dynamics.

Considering the mass of water $\varepsilon(t)$ contained in the ballast tank, a standard six-dimensional model for the rigid body motion (plus the “ballast’s dynamics”) can be obtained as follows.

\[
\dot{\mathbf{v}} = J(\varepsilon) \cdot \mathbf{v} \quad (2a)
\]

\[
M(\varepsilon) \dot{\varepsilon} + C(v, \varepsilon) \varepsilon + D(v) \varepsilon + g(\varepsilon, \varepsilon) + T(v, \varepsilon) \dot{\varepsilon} = \tau \quad (2b)
\]

\[
\dot{\varepsilon} = u_c \quad (2c)
\]

where the mass matrix $M(\varepsilon)$, the Coriolis matrix $C(\varepsilon)$ already include the added mass effects (Fossen [2002]), $D(v) \varepsilon$ is the hydrodynamic drag force acting on vehicle, $g(\varepsilon, \varepsilon)$ indicates the forces of gravity and buoyancy, and the term $T(v, \varepsilon) \dot{\varepsilon}$ represents the effects of the variable CoG (1). In (2c) we assume that we can control the velocity of the CoG $\dot{\varepsilon}$ via the input $u_c$. The generalized force $\tau$ consists on the (controlled) hydrodynamic effects of the wings, characterized later on.

This modeling technique for vehicles having a variable position of the CoG has been also used in (Caiti and Calabrò [2010]) for a hybrid AUV, see (Caffaz et al. [2012]) for further details. In Table 2 the numerical parameters here used are shown.

<table>
<thead>
<tr>
<th>Characteristic Glider parameters</th>
<th>Length</th>
<th>2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.15 m</td>
<td></td>
</tr>
<tr>
<td>Static weight $m_s$</td>
<td>23.65 kg</td>
<td></td>
</tr>
<tr>
<td>Static CoG position $(\Lambda/m_s)_{x}$</td>
<td>$-0.02$ m</td>
<td></td>
</tr>
<tr>
<td>Static CoG position $(\Lambda/m_s)_{y}$</td>
<td>0 m</td>
<td></td>
</tr>
<tr>
<td>Static CoG position $(\Lambda/m_s)_{z}$</td>
<td>0.1 m</td>
<td></td>
</tr>
</tbody>
</table>

### 2.1 Ballast tank characterization

We assume that the position of the CoG can vary only by filling and emptying the ballast tank.

Based on the numerical parameters of Table 2, we “characterize” the ballast actuator, positioned on top of the vehicle’s hull. Therefore, injecting water in the ballast tank will result in moving the CoG towards the top of the vehicle, and vice versa.

This choice also allows to regulate the pitch angle of the vehicle by changing the water contained in the ballast tank. As a consequence, also the glide angle of the vehicle can be regulated.

Buoyancy force of the vehicle depends linearly on the amount of water embarked in the ballast tank. The positioning of the ballast tank has been tuned in such a way that some symmetry is obtained for the buoyancy: for values of water mass $\varepsilon > 0.5$ kg the vehicle becomes negative (the gravity force is greater than the buoyancy force), while for $\varepsilon < 0.5$ kg the vehicle is positive (the gravity force is less than the buoyancy force).

By introducing a certain mass of water $\varepsilon$ in the ballast tank at the position $r_w$ we obtain a shift of the CoG of the entire vehicle, as represented in Fig. 1.

### 2.2 Wings characterization

The hydrodynamic wings play a fundamental role to guarantee the gliding motion of the vehicle. Their contribution affects the dynamics (2b) via the generalized force $\tau$.

For “numerical convenience”, we consider the NACA009 wing profile.

The orientation of each wing is described by the angle of attack $\alpha + \beta$, see Figure 3, i.e. the angle between the longitudinal direction of the wing $x_w$ and the direction of the velocity $v_w$.

A hydrodynamic wing introduces the lift $L(\alpha + \beta)$ and drag $D(\alpha + \beta)$ forces, see Figure 3, due to its relative velocity with respect to the fluid velocity.
3. UNDERWATER GLIDING CONTROL PROBLEM

The gliding control problem we address here is the problem of finding a state-feedback control law $u_w(\eta, \nu, \varepsilon)$ and the wings orientation $\alpha$, affecting $\tau = \tau(\alpha)$, such that a certain motion is achieved by the vehicle.

We notice that setting the wings orientation angle $\alpha$ to zero, we achieve the same maneuverability of a glider with fixed wings. Hence we claim that this additional degree of freedom can be actually exploited, especially if the wings are independently controlled.

Now, let us also notice what happens if the wings orientation angle $\alpha$ is fixed to zero. In this case, we have that, see Figure 5, the equilibrium glide angle reached by the vehicle is quite “small” if the amount of water contained in the ballast tank is close to its central value, that is $0.5 \text{ kg}$. On the contrary, the vehicle can achieve larger gliding angles whenever we have values of water mass $\varepsilon$ far from the central value.

Note that, in general, the control of the wings positioned in the tail of the vehicle is not a trivial task because the system suffers of “coupling effects”. In fact, any control input on the wings introduces additional moments along the pitch axis, while the differential control strategy introduces moments along the pitch and the roll axes.

3.1 Preliminaries on the path-following problem

The high-level control strategy used in this work is based on the path-following method ([Breivik and Fossen 2005]). We indeed refer to this reference for the details on the definition of the path-following problem.

In this paper we consider the following approximations ([Chwang and Wu 1975]) for such induced forces:

$$ L(\alpha + \beta) = \frac{1}{2} \rho V^2 SC_L (\alpha + \beta) $$

$$ D(\alpha + \beta) = \frac{1}{2} \rho V^2 SC_D (\alpha + \beta) $$

where $\rho$ is water density, $V$ is the wings speed in the fluid, $S$ is the area of wings surface, while the terms $C_L$ and $C_D$ are dimensionless coefficient depending on the chosen wings profile and also on the wings angle of attack.

The peculiarity of the method in ([Breivik and Fossen 2005]) is the development of control laws for a generic ideal model of vehicle, according to the following (backstepping) steps: (a) a point on the vehicle (“actual particle”) tracks a desired trajectory; (b) a control is constructed to achieve the desired speed computed above.

This strategy is typical of path-following problems as, unlike trajectory-tracking problems, no time limitations are considered. The actual particle chosen is the CoG, and the goal here is its convergence to the most convenient “path particle”, also named “ideal particle”.

In our case, the references are the pitch and the yaw angles of the velocity of the ideal particle. The control scheme is presented in Fig.4. The model dynamics (2b) are implemented in the block Dynamics.

The Feedforward block solves the step (a) of the path-following problem described above, in the sense that it computes the distance between the actual particle and the ideal particle, together with the state errors $\bar{\eta}, \bar{\nu}, \bar{\varepsilon}$. The Feedback block solves the step (b), namely it uses such values to generate the state-feedback control actions.

3.2 Switching state-feedback velocity control

In the Feedback block, a switching control is implemented in order to limit the chattering behavior of the ballast actuator close to the equilibrium point. The latter phenomenon would be definitively undesired because, from the practical point of view, actuating the ballast tank at “high” frequency is particularly inefficient from the energy-consumption point of view.

Technically, we propose a feedback control of the amount of water in the ballast tank that is purely proportional far from the desired path:

$$ u_{a} (\bar{\eta}, \bar{\nu}, \bar{\varepsilon}) = \begin{cases} 0.1 \cdot \text{sat}(K \bar{\varepsilon}) & \text{if } \|(\bar{\eta}^T, \bar{\nu}^T)\| \leq \bar{\varepsilon} \\ 0 & \text{otherwise} \end{cases} $$

$$ (\bar{\eta}, \bar{\nu}, \bar{\varepsilon}) = (0, 0, \varepsilon) \Rightarrow (0, 0, 0) $$

Fig. 3. Lift and drag forces generated by the hydrodynamic wings as a function of the angle of attack of the hydrodynamic wings themselves.

Fig. 4. Backstepping control scheme. The feedforward block computes the reference signals and hence the state errors. The feedback block implements the control laws to track the reference signals.
where $K_s \in \mathbb{R}$ is the feedback gain and $\bar{c} \in \mathbb{R}^+$ is a certain threshold to be tuned.

Namely, whenever the vehicle is “close enough” to the desired path, the control of the ballast tank is disabled to avoid the ballasting chatter and only the wings are used to finely reach the desired path.

### 3.3 Optimization-based wings control

According to the force characterization of the hydrodynamic wings, see Section 2.2, the generalized force $\tau$ applied to the vehicle’s CoG is

$$
\tau = B(\beta, \alpha, V) \alpha, \quad (6)
$$

where $B(\cdot)$ is a nonlinear function of the angles $\beta = (\beta_1, \beta_2)^T$, of the angles $\alpha = (\alpha_1, \alpha_2)^T$ and of the wings-velocities moduluses $(V_1, V_2)^T = V \in \mathbb{R}^2$. The nonlinear function $B(\cdot)$ comes from the forces of lift $L(\cdot)$ and drag $D(\cdot)$ forces that are shown in Figure 3.

The objective here is indeed the choice of $\alpha$ to recover the desired generalized force $\tau$, or a close approximation of it, according to equation (6).

For simplicity, in the control synthesis we neglect the drag terms because of about one order of magnitude smaller than the lift ones (in the desired operating conditions). Therefore, we consider an approximate nonlinearity:

$$
\bar{\tau} = \bar{B}(\beta, \alpha, V) \alpha, \quad (7)
$$

with $\bar{B}(\beta, \alpha, V) \in \mathbb{R}^{2\times 2}$ and $\bar{\tau} = (\tau_3, \tau_6)^T$.

We choose this two components because the velocity angles of pitch and yaw are used as references.

In order to obtain a good convergence, an integral term is introduced “close” to the desired path:

$$
\tau^*(\bar{\eta}, \bar{\nu}, \bar{e}) =
\begin{cases}
K_p \cdot \left( \begin{array}{c} \bar{\eta} \\ \bar{\nu} \end{array} \right) & \text{if } \left\| (\bar{\eta}^T, \bar{\nu}^T) \right\| \leq \bar{e} \\
K_p \cdot \left( \begin{array}{c} \bar{\eta} \\ \bar{\nu} \end{array} \right) + K_i \int \left( \begin{array}{c} \bar{\eta}(t) \\ \bar{\nu}(t) \end{array} \right) dt & \text{otherwise}
\end{cases}
$$

where $K_p$ and $K_i \in \mathbb{R}^{2\times 2}$ are constant matrix gains to be tuned.

A possible way to regulate the wings angles $\alpha$ is to solve an optimization problem online. Given the current angles $\alpha_0, \beta_0$, the current velocity moduluses $V_0$ and a desired force $\tau^*$ to be reproduced, the angles $\alpha$ can be chosen as follows.

$$
\alpha := \arg\min_{x \in \mathbb{R}^2} \left\{ s(x)^T Q s(x) + (x - \alpha_0)^T R (x - \alpha_0) \right\}
$$

subject to:

$$
\alpha \leq x \leq \overline{\alpha}, \quad \Delta \alpha \leq x - \alpha_0 \leq \overline{\Delta} \alpha
$$

where:

$$
s(x) := \tau^* - \bar{B}(\beta_0, \alpha, V_0) \alpha.
$$

The bounds $\alpha, \overline{\alpha}, \Delta \alpha, \overline{\Delta} \alpha$ are free design parameters reflecting the physical limits on the wings actuators. The weight matrices $Q, R$ are positive definite. The problem (9) is a nonlinear optimization problem as $s(x)$ is a nonlinear function of $x$.

Following the approach proposed in (Johansen et al. [2004]), we consider a linearized version of problem (9) leading the following Quadratic Problem (QP) to be solved online.

$$
\alpha := \arg\min_{x \in \mathbb{R}^2} \left\{ s(x)^T Q s(x) + (x - \alpha_0)^T R (x - \alpha_0) \right\}
$$

subject to:

$$
\alpha \leq x \leq \overline{\alpha}, \quad \Delta \alpha \leq x - \alpha_0 \leq \overline{\Delta} \alpha
$$

where:

$$
s(x) := \tau^* - \bar{B}(\beta_0, \alpha_0, V_0) \alpha_0 - \left[ \frac{\partial}{\partial \alpha} (\bar{B}(\beta_0, \alpha, V) \alpha) \right]_{(\beta_0, \alpha_0, V_0)} \cdot (x - \alpha_0).
$$

Note that, unlike (Johansen et al. [2004]), the approximation of the original nonlinearity $\bar{B}(\cdot)$ in (6) with $B(\cdot)$ in (7) is such that $\bar{B}(\beta, \alpha, V)$ is never singular. Within this simplifying reduction, there is no need to address the problem via sequential QPs.

### 4. SIMULATIONS

Many numerical simulations have been performed in order to tune the free design parameters and also to validate the proposed switching-control strategy. We noticed that in our backstepping control scheme, an undesired chattering behavior of the ballast actuator would be generated without the use of the proposed switching strategy.

Our simulation experience confirms what basic intuition would suggest: the action of the ballast tank is more relevant to regulate the pitch variable, while the corrections determined by the independently-controlled hydrodynamic wings play a relevant role in regulating the yaw variable. Basically, a differential control of the hydrodynamic wings allows to generate roll and yaw motions.

The numerical parameters used in the implemented QP are $\alpha, \overline{\alpha} = \pm 15$ deg, $\Delta \alpha, \overline{\Delta} \alpha = \pm 5$ deg, $Q = I$, $R = 20I$.

We present here the gliding motion of the glider, shown in Figure 6, that has to follow an helical trajectory of radius 40 m, see Figure 7. Such trajectories are particularly efficient to explore and sample underwater sink holes (Andonian et al. [2010a,b]). The initial vehicle states are $\eta_0 = (0, 70, -20, 0, 0, 0)^T$ and $\nu_0 = (0.05, 0, 0, 0, 0, 0)^T$. Fig. 5. Steady-state glide angle reached by the vehicle as a function of the water contained in the ballast tank positioned on top of the vehicle’s hull.
5. CONCLUSION

In this paper we have presented a control-oriented model of an underwater glider with independently controllable hydrodynamic wings. Through the use of a ballast tank and of the hydrodynamic wings, a simple, backstepping, control scheme has been presented to accomplish some particular three-dimensional path-following maneuvers. We have used a switching control scheme to avoid the undesired chattering of the ballast tank actuator whenever the vehicle gets close to the desired path. The control algorithm is validated via numerical simulations. We remark that our switching control law is only justified by simulations heuristics, not by theoretical analysis.

The provided example shows the potentialities of using independent actuations for the hydrodynamic wings. In particular, the actuation of the ballast tank can be limited by just exploiting the corrections of the wings. This would
further increase the energy efficiency of underwater gliders, even if non-trivial maneuvers are to be performed.

Therefore we expect that this work can motivate further research studies on the design of more accurate control schemes exploiting the independent actuation of the hydrodynamic wings, besides the physical realization of glider prototypes of the kind here described.

From this latter point of view, it would be remarkable the realization of a prototype capable of exploiting its hydrodynamic wings together with the waves energy for the surface navigation, and together with the oceanic currents for the underwater navigation.

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