Guidance and Control of an Autonomous Underwater Glider

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Abstract

This paper describes an approach to the guidance and control system design of an underwater glider. We focus on the critical phase between ascent and descent of the glider in the presence of disturbances due to currents. The control and guidance system we propose is based on a L-G controller of the guidance dynamics and on a sliding mode controller of the motion dynamics. The robustness of the system is illustrated through simulations.

Introduction

Underwater gliders use passive propulsion systems, based on the transformation of gravity (or Archimede) forces to forward thrust by the mean of large lifting surfaces, at the price of a control of buoyancy and pitching angle. It has been demonstrated (see [1]) that above a certain depth (which value may depend on the buoyancy and pitch actuator design), gliders have lower energy requirements than propeller equiped vehicles. The limitations of such vehicule are first that they are constrained to travel along ascending and descending gliding trajectories and second that they operate at low speed. However, for applications that does not require survey at constant depths and for which relative speed is not a limiting factor, gliders seems to be an adequate solution. In particular for oceanography applications (for instance, thermocline investigation with ctd sensors), the use of underwater glider is envisionned in short term.

In this paper, we are interested by the control of the guidance and motion dynamics of a glider operating in the vertical plane. The typical path of a glider is a sequence of ascending or descending paths at constant glide slope. The problem we are interested in is related to the transition phase between an descending path and an ascending one. During this phase, two controls are used:

- Buoyancy, which will vary (generally in open loop control) from a positive value to its opposite value,
- Pitch, which is used for controlling (in closed loop) the relative path.

The main difficulty is to achieve a relative path reference trajectory whislt keeping the relative velocity above a critical valued under which the glider becomes uncontrolable.

The paper is organized as follows: In section 1, we present an approach for guidance system design, based on the design of a L-G (Leitmann-Gutman) controller of the glider relative angle. Section 2 is devoted to the design of a motion dynamics controller that achieves tracking of a guidance reference trajectory. A short description of the "Sterne" Glider developped at Ensieta is postponed in appendix 3.

1 Guidance problem

1.1 Problem statement

The guidance scheme we propose is a control law of the relative path angle of the glider by the *angle of attack*. As we restrict our study to the vertical plane motion, the dynamics model we use is the following:

$$\left\{\begin{array}{lcll} x' & = & V\cos\gamma + W_x & x \in [0, +\infty[\\ z' & = & -V\sin\gamma + W_z & z \in [0, -\overline{z}] \\ V' & = & \frac{1}{m_e}\left[-D(\alpha, V) - (m_s g - B)\sin\gamma\right] - (W_x'\cos\gamma - W_z'\sin\gamma) & V \in [\underline{V}, \overline{V}] \\ \gamma' & = & \frac{1}{m_e V}\left[L(\alpha, V) - (m_s g - B(t))\cos\gamma\right] + \frac{1}{V}(W_x'\sin\gamma + W_z'\cos\gamma) & \gamma \in [\underline{\gamma}, \overline{\gamma}] \\ m_s'(t) & = & v(t) & m_s \in [\underline{m_s}, \overline{m_s}] \end{array}\right. \tag{1}$$

where

- x and z are the glider position and depth,
- V is the relative velocity with respect to the ambiant fluid
- γ is the relative path angle (see figure 1).

Here α denotes the angle of attack. It is considered as the control, and subject to given bounds, e.g $\alpha \in [\underline{\alpha}, \overline{\alpha}]$. Buoyancy control is denoted by $v(t)$, and is be supposed to be known (in open loop) for a given manoeuver.

Current is denoted by $W = (W_x, W_z)$, and $W' = (W'_x, W'_z)$ denoted its time derivative. In the following, W and W' will be supposed to by known by its bounds and no information on the structure of the current field is supposed to be known.

Figure 1 shows the coordinate system and free body diagram. System (1) is composed by two kinematics equations. The dynamics equations are taken relative to a moving but nonrotating reference frame, translating with the current velocity at the glider center of mass (see [3]). It can be supplemented with lift and drag models, which contains the lift and drag contribution of both wings and central body of the glider:

$$
\begin{array}{rcl}
D(\alpha, V) & = & \frac{1}{2}\rho(S^b(\mathrm{CD}_0^b + \mathrm{CD}_1^b\alpha^2) + S^w(\mathrm{CD}_0^w + \mathrm{CD}_1^w|\alpha| + \mathrm{CD}_1^w\alpha^2))V^2 \\
L(\alpha, V) & = & \frac{1}{2}\rho(S^b\mathrm{CL}_0^b + S^w\mathrm{CL}_0^w)\alpha V^2
\end{array}
$$

where

S^b	:	surface of the Glider central body,
S^w	:	total surface of the Glider wings,
$\mathrm{CD}_0^b, \mathrm{CD}_1^b$	:	Drag coefficient of the central body,
CL_0^b	:	Lift coefficient of the central body,
$\mathrm{CD}_0^w, \mathrm{CD}_1^w, \mathrm{CD}_2^w$	:	Drag coefficient of wings,
CL_0^w	:	Lift coefficient of wings.
ρ	:	specific gravity of water.

1.2 Guidance system design using a L-G controller

In this section, we consider the problem of tracking the relative path angle $\gamma(t)$ to a specified trajectory $\gamma_R(t)$. We shall denote the tracking error by :

$$\Delta\gamma(t) = \gamma(t) - \gamma_R(t) \tag{2}$$

The objective is to keep $\Delta\gamma(t)$ as close as possible to zero, in the presence of current disturbances.

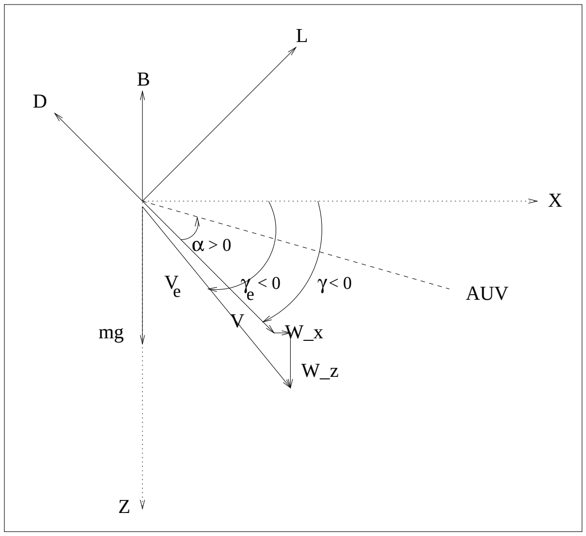


Figure 1: Coordinate system. The dashed line is the Glider reference line. γ_e and V_e are respectively path inclination and gound velocity.

Denoting by $\mathrm{Scl} = S^b \mathrm{CL}_0^b + S^w \mathrm{CL}_0^w$, we have from (1):

$$\Delta\gamma' = \frac{\rho V \mathrm{Scl}\alpha}{2m_e}$$

$$\frac{(m_s(t)g - B)\cos(\Delta\gamma + \gamma_R)}{m_e V} + \frac{W_x' \sin(\Delta\gamma + \gamma_R) + W_z' \cos(\Delta\gamma + \gamma_R)}{V} - \gamma_R' \tag{3}$$

The controller is composed by a feedforward term which aim is to cancel the nominal dynamics of $\Delta\gamma$:

$$\alpha_{\mathrm{no}} = \frac{2\left[(mg - B(t))\cos\gamma + mV\gamma_R'\right]}{\rho V \mathrm{Scl}} \tag{4}$$

Then, we determine the control $\alpha(t) = \alpha_{\mathrm{no}}(t) + \Delta\alpha(t)$ by using the method used in [4]. System (4) can be viewed as an uncertain system (due to the presence of current disturbances W_x', W_z' with matched uncertainty. We use a L-G controller which synthesis require the knowledge of the bounds of the uncertainty These controllers have the practical stabilization property; namely the state of the system can be driven in a neighborhood of the origin, the size of which can be chosen arbitrarily small. The relative path inclination controller we obtain is the following:

$$\Delta\alpha(t) := \frac{-\eta(\Delta\gamma)\zeta}{|\eta(\Delta\gamma)| + \varepsilon}$$

where ε is a design constant, $\eta(\cdot)$ and ζ are functions depending of the uncertainty bounds and the minimum and maximum relative velocities $(\underline{V}, \overline{V})$.

1.3 Numerical simulation results

The guidance algorithm has been implemented and tested for various parameter configurations, and for various disturbance models. Figure (2) and (3) show runs of the guidance algorithm in the following configuration:

Reference gliding angle	:	14 deg
Initial gliding angle	:	10 deg
Initial relative velocity	:	0.9 m/s
Initial angle of attack	:	0 deg
Bound on derivative of the angle of attack	:	0.25 deg/s
Maximum depth	:	50 m
Vertical current disturbance	:	$W_z(t) = a(z)\sin(bt)$
Horizontal current disturbance	:	$W_x(t) = W_x$

In figure (2), one sets $W_x = 0.5$, $a(z) = (-z/50 + 1)/10$ and $b = 30$ which corresponds to an oscillating current heave velocity with damping at the seabed (supposed to be here at50meter depth).

In figure (3) no disturbance is considered. One can check the robustness of the LG-controller based guidance system in comparing these two simulation results.

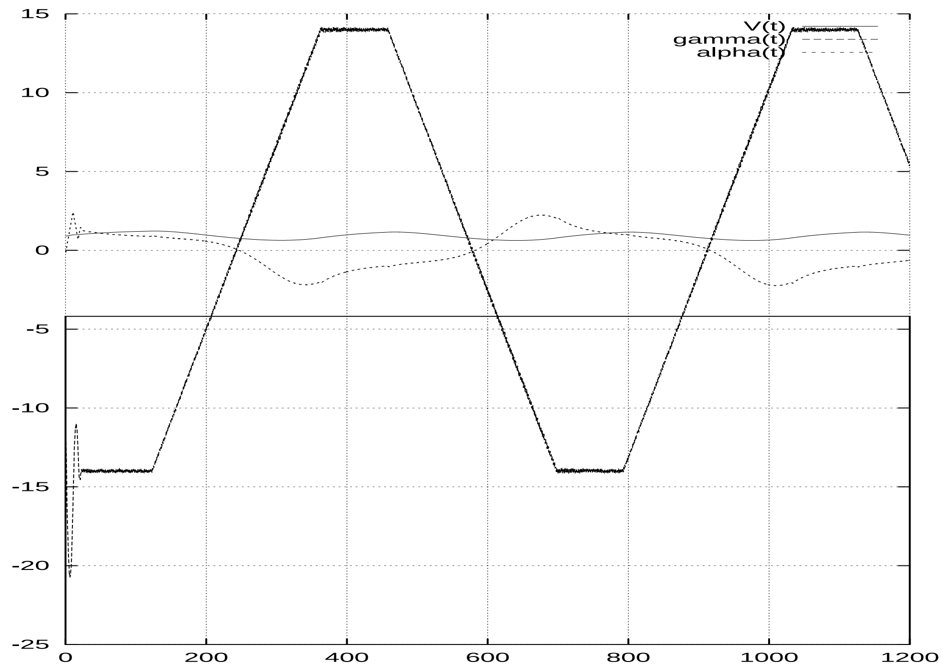
2 Motion control problem

2.1 Problem statement

The guidance system presented above produces a control α, which achieves tracking of the relative path angle of the glider to the reference path angle γ_R. In this approach, α was considered as a control, subject to a chattering bound $|\alpha'| \leq C$.

The problem is now to design an actuator control system desgin which achives the trajectory produced by the guidance control system. Thus, the guidance reference trajectory is now considered by a state space reference

Figure 2:



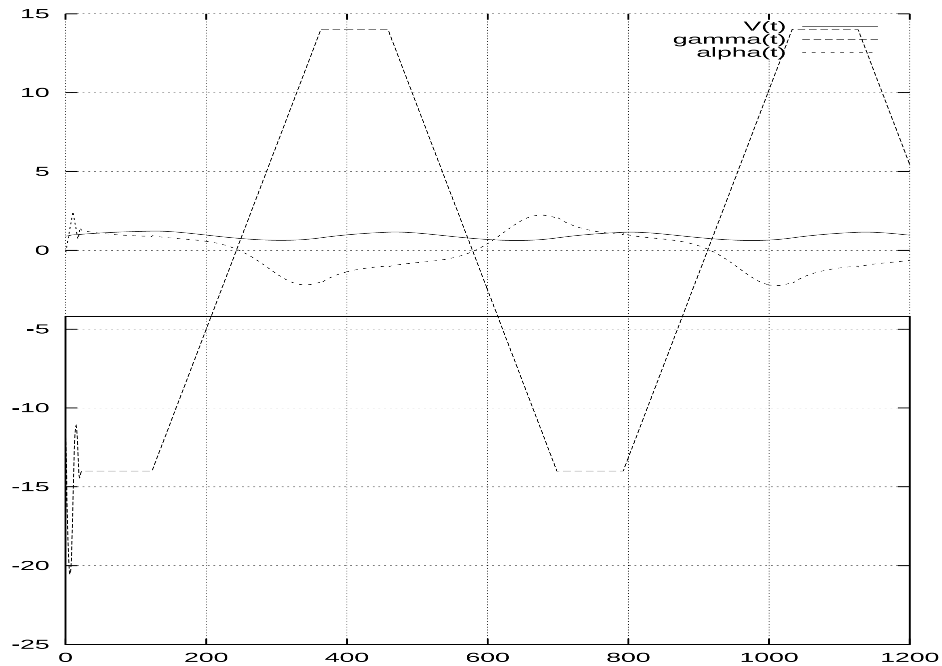
trajectory of the glider motion dynamics. The motion dynamics we consider is the following:

We consider the state variable (u, w, q) where u is the surge velocity, w the heave velocity, and q the pitch velocity.

$$
\begin{array}{lcl}
(m(t) - X_{u'})u' & = & X_b(u,w) + (W(t) - B)(-\sin(\theta)) + X_w \\
 & & -w(t)q(m - Z_{w'}) + mX_G q^2 + X_P \\
(I_y - M_{q'})q' & = & (BZ_B - W(t)Z_G)\sin(\theta) + (BX_B - W(t)X_G)\cos(\theta) \\
 & & +Z_w x_w^h + (X_{u'} - Z_{w'})wu + mX_G(-uq) \\
\theta' & = & q
\end{array}
$$
(5)

The following notations are used:

Figure 3:



X_b	:	projection of the hydrodynamics forces of the body and fixed wings along the longitudinal axis.
X_w	:	projection of the hydrodynamics forces of the rear fins along the longitudinal axis.
Z_w	:	projection of the hydrodynamics forces of the rear fins along the vertical axis.
$W(t), B$	:	weight and buoyancy of the glider.
Z_G, Z_B, X_B	:	coordinates of the center of buoyancy and of the center of gravity.
x_w^h	:	coordinate of the rear fins along the longitudinal axis
$X_{u'}, M_{q'}, Z_{w'}$		

The control we use are the position of the center of gravity along the longitudinal axis X_G, and the propulsion force X_P. It should be mentionned that X_P is only used for reaching a certain level of relative velocity.

Here, the heave velocity $w(t)$, and the time varying inertia $m(t)$ are considered as external inputs to system (5)

A typical desired trajectory consists of two distinct phases:

- A target problem which objective is to reach a desired surge velocity u

and relative path angle at minimum angle of attack and with $W(t) = B$,

- A serie of ocsillating paths, for which $W(t)$ is controlled in open loop. The control X_G is used to achieve the reference trajectory produced by the guidance system. In this phase, $X_P = 0$.

2.2 Dynamics control of the relative path

Model (5) can be controlled by using a sliding mode controller of u and θ. For the surge velocity u, we use a first order controller. For θ, we use a second order controller. Namely, we define two sliding surfaces by

$$S_1(u) = u - u_d$$

and

$$S_2(\theta, \theta') = (\theta - \theta_d)' + \lambda(\theta - \theta_d)$$

where λ is a design parameter and u_d, θ_d are the desired surge velocity and pitch angle. The desired pitch angle is determined by the guidance controller angle of attack output: $theta_d(t) = \gamma_R(t) + \alpha(t)$.

We can write the dynamics (5) by

$$\begin{array}{lrcl} (6) & u' & = & f_1(u,\theta,q;w) + g_1(u,\theta,q;w)(XG,XP)^T \\ & q' & = & f_2(u,\theta,q;w) + f_2(u,\theta,q;w)XG \\ & \theta' & = & q \end{array}$$

where the quantity w is considered as a known external disturbance. Moreover, we can consider this system as a cascade control system in controlling the pitch equation by the center of gravity position XG, and then controlling the surge equation with given XG. This can be done by two sliding mode controllers composed of two terms:

- An equivalent control (XG_{eq}, XP_{eq}) which achieves perfect trakcing of u, q, θ with the asumption that no disturbance acts on the system;

- An additive discontinuous term, which take into accounts the presence of disturbances or uncertainities on the above dynamics.

Finally we can determine a control of the type

$$\begin{array}{lrcl} (7) & XG & = & XG_{eq}(u,\theta,q;w;q_d,q_d') + K_{XG}\mathrm{sat}(S_2(\theta,\theta')) \\ & XP & = & XP_{eq}(u,\theta,q;w;XG;u_d,u_d') + K_{XP}\mathrm{sat}(S_1(u)) \end{array}$$

where sat$(\cdot)$ denotes a saturation function which approximates the sign function.

Here, K_{XG} and K_{XP} can be determined in such a way that the discontinuous part of the controller achieves finite time attractivity of the sliding surface (or more precisely of a neighborhood of the sliding surface) in the presence of disturbances and parameter uncertainty.

2.3 Numerical simulation results

Figure 4:

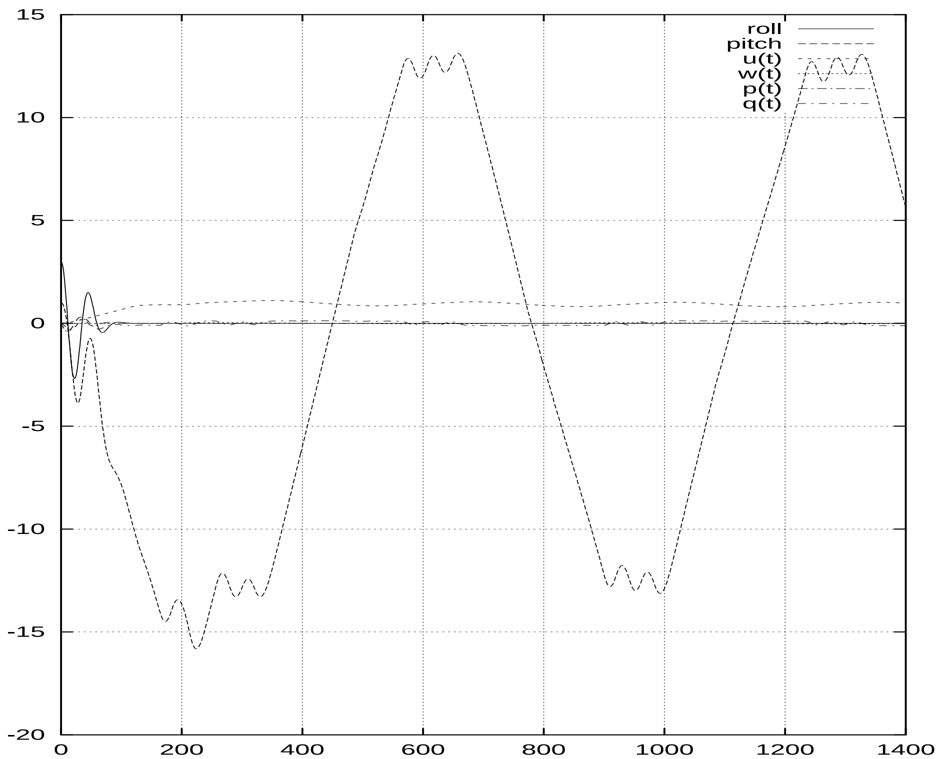


Figure (4) shows a numeraical simulation result of the motion dynamics controller. It has been obtained in the following configuration:

- The initial roll is set to 3 degrees (and here considered as a non modelled disturbance).
- The first phase (target problem) used to reach the desired velocity is active during the first 100 seconds.

- The reference trajectory for gliding pathes is taken as the output of the guidance controller (see figure (2)).
- The sampling time has been set to 0.1 second in order to take into accounts actuator dynamics.
- Uncertainty on dynamics coefficients is 10% in average.

One can check that despite the uncertainty on the dynamics and the initial disturbance on roll, the motion controller tracks the guidance reference path with acceptable accuracy. One can observe that the roll dynamics damps without roll control, as the glider is naturally stable. Ocsillations of the pitch angle are due to the limitation of the center of gravity velocity.

3 Concluding remarks

An approach based on robust control of guidance and control of an underwater glider has been presented. Through numerical simulation, we can conclude that the guidance and control system we designed offers good performances in term of robustness to dynamics uncertainty and to currents. Integration of this system is currently in progess in the "Sterne" glider developped at Ensieta.

Appendix: The Sterne Glider

The Sterne glider is in developpment at Ensieta since 1998. It is designed for long endurance missions, as well as for surveys close to the seabed. Indeed, in addition to a "classical" glider configuration, it is equiped with a thruster. Figure (5) shows a CAD view of the Sterne:

- The rear section contains three fins actuators equipped with integrated lift and drag sensors, a thruster mounted on a force sensor, a hydrostatic pressure gauge, and a electronics container. A GPS antenna is fixed at the top of the rear rudder.
- The central section contains a battery set mounted on a movable rack, tanks for ballasting, three computer racks, and power supply.
- The nose section contains a motion reference sensor, a Doppler loch, an obtacle avoidance sonar, an vertical echosounder.

The vehicle is 4.5 meter long, has a diameter of 0.6 meter. It weights 990 kg dry, and has an inertia of 1350 kg in water.

The Sterne is equipped with a pair of large wings fixed at the center of the central section, a pair of movable fins at the rear, and a movable rudder. Its ballast, used for buoyancy control, has a maximum capacity of 40 liters.

Three main computers, and a CAN network are integrated in the Sterne. The first computer is devoted to mission control, the second one to navigation, guidance, and dynamics control, and the third one to obstacle avoidance. A CAN bus connects a set of processors that are attached to each sensor and actuators. They are devoted to preprocessing of data (filtering, signal conditionning, communication with sensors, diagnostic of sensor, force control of actuators).

A 1/3 model has been tested in free flight, for performance assesment. These tests have been performed in a 50 meter long an 10 meter depth with the support of Ifremer (Brest). Picture (6) shows the Sterne model during one of its free flight, in ascending mode. The minimum relative path angle of the Sterne has been determined through intensive tank tests. It is around 13 degrees. Based on this data, we estimate that with a set of 12 conventionnal Lead/Acid batteries, the maximum range of the Sterne is 120 Nautical miles.

References

[1] A. BAZ, A SEIREG. Optimum Design and Control of Underwater Gliders. *Transactions of the ASME*, pp 304-310, Feb 1974.

[2] A.GALEA. Various Methods for Obtaining the optimal path for a glider vehicle in shallow water and high currents *UUST Proceedings*, pp 150-161, 1999.

[3] A. MIELE, T. WANG and W.W. MELVIN. Guidance Strategies for Near-Optimum Take-Off Performance in a Windshear. *Journal of Optimization Theory and Applications*, 50(1), 1986.

[4] G. LEITMANN and S. PANDEY. Aircraft Control Under Conditions of Windshear. *Control and Dynamic Systems*, Vol.34, 1990.

[5] P.J SIMONETTI. Low cos, Endurance Ocean profiler. *Sea Technology*, Feb 1998..

[6] D.C. WEBB, P.J SIMONETTI. The Slodum AUV: An environmentally propelled underwater glider. *UUST Proceedings*, pp 75-85, 1999.

[7] D.C. WEBB, P.J SIMONETTI. A simplified approach to the prediction and optimization of performances of underwater gliders. *UUST Proceedings*, pp 50-68, 1997.

Figure 5: CAD view of the STERNE glider

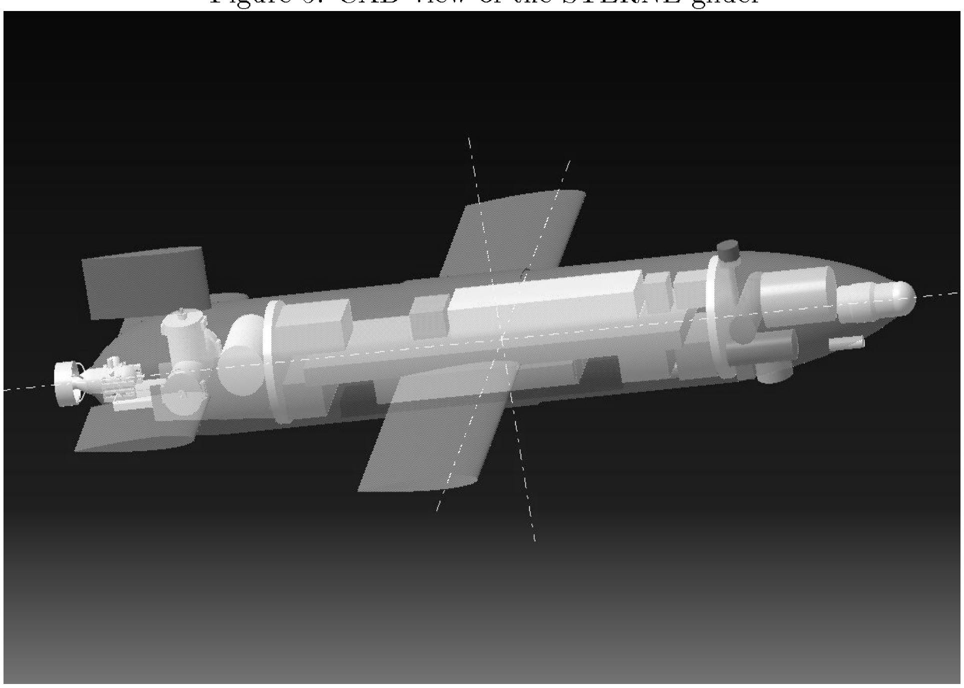


Figure 6: Tank test of the STERNE glider model (ascending path, near the surface)