

Heading control of an autonomous underwater robot with sliding mode and backstepping techniques

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ABSTRACT

The variation of the parameters of the autonomous underwater robot (inertia, hydrodynamics), external disturbances, the non-linearity of the model to be controlled, and measurement errors due to the sensors are the factors that have a negative influence on the robot's trajectory following. Autonomous submarine. A control law that takes these different factors into account would be an adequate solution to this control problem. This work is a simulation study of some advanced control techniques for controlling the heading of an autonomous underwater robot. We have developed two robust command structures. One of them is based on the sliding-mode control, which is applied to the considered model. The other is based on the control of backstepping. Several simulation tests were done to see how the robot moved after the two control methods were used.

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1. INTRODUCTION

About 70% of the earth's surface is covered with water and its influence is crucial in all respects. The last half-century of oceanographic research has shown that the ocean and the seabed hold the keys to understanding many of the processes responsible for the formation of our planet. Exploration of the marine environment has provided valuable knowledge to many fields of science and engineering [1]. For this, marine robotics has experienced phenomenal growth in various scientific, civil, and military applications. These applications include three main categories: inspection and surveying; seek and save; surveillance and security [2], [3].

Autonomous underwater robots normally have a torpedo shape and are capable of maneuvering autonomously without constant real-time control from the operator. Autonomous underwater robots can operate freely with the missions and control strategy configured in advance [4]. They are widely used in ocean engineering and are designed to be effective for long-range and large-scale survey missions [5].

Taking into account the various constraints of the surrounding environment, the non-linearity of the model, the uncertainties of the parameters linked to the autonomous submarine robot, and conventional linear type controls, in particular of the PID type [6], [7] have shown their limits. Faced with this situation, research has been carried out on the development of non-linear controls. One can cite among others the control by Backstepping, the control with variable structures, etc. The problem is to move the robot from a starting point to an ending point by following a heading trajectory, the sliding mode control is a control that presents much more important advantages because of its simplicity and its robustness [8], [9]. in the face of disturbances, uncertainties, and non-linearities of the system. However, this solution has drawbacks due to the phenomenon of chattering. To reduce this phenomenon, different techniques can be found in the literature, namely: the

solution of the introduction of a transition band around the sliding surface to transform the sign function into saturation, or the substitution of the sign function by others with softer variation, the use of the boundary layer, a solution based on higher-order sliding modes [10]–[12].

Backstepping offers a systematic method to find a control law, the idea of the latter is to design a regulator step by step, considering certain state variables as virtual commands [13]–[15]. The order is found from the final step. Unfortunately, this technique is based on the knowledge of the model, which presents a disadvantage, because a variation in the dynamic model can be interpreted directly by an increase in the tracking errors. The work presented in this article focuses on the synthesis of two nonlinear control techniques: Backstepping control and sliding mode control. We will discuss the simulation results of these two types of rules on the torpedo-type autonomous underwater robot to conclude at the end which type of control is the most appropriate and which gives the best behavior for our system studied in this article.

2. MATHEMATICAL MODELING

The equations of motion for underwater vehicles can be presented concerning a Body-fixed frame relative to an Earth-fixed frame represented by the Figure 1. The modeling of the autonomous underwater robot is done in two parts: kinematics and dynamics. The kinematic model deals with the geometric aspects of movement, and the dynamic model analyzes the effect of the forces and moments that generate the movements. the latter is modeled by five models: we have the dynamic model of a rigid body, the model of the actuators (thrusters and control surfaces), and because we are in an aquatic environment, we have two new models: the hydrostatic model when the robot is stationary in the water and the hydrodynamic model when the robot is moving in the water [5], [10], [16]. The nonlinear vehicle equation of motion is written as [5], [16]:

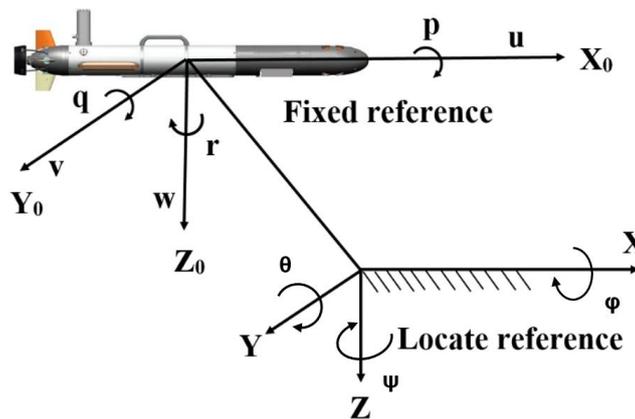


Figure 1. The autonomous underwater robot and its representational landmarks

$$\begin{cases} M\dot{v} + C(v)v + D(v)v + g(\eta) = \Gamma \\ \dot{\eta} = J_c(\eta_2)v \end{cases} \quad (1)$$

With, M: are the inertia matrix of the dynamics system and the added water mass, C: is the matrix of applied and hydrodynamic Coriolis and Centrifuge forces, D: is the matrix of the damping forces, g: the vector of hydrostatic forces, Γ : the vector of forces and moments generated by all of the robot's actuators. Hence, the global state vector is represented by: $(\eta, v) = [x \ y \ z \ \phi \ \theta \ \psi \ u \ v \ w \ p \ q \ r]^T$. With vector η groups together x, y, and z being the three position components, the three orientation components are defined as follows: ψ : represents the yaw angle, ϕ : represents the roll angle, and θ : represents the pitch angle. and vector v groups the velocity components of the robot.

In this article, we are interested to study the behavior of the autonomous underwater robot in a yaw plane, so we only need the yaw angle (ψ), linear velocity (v) and angular velocity (r). Then we considered the other variable's states as null. The mathematical model in the yaw plane is represented, from (1):

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.209 & -0.605 & 0 \\ -0.054 & -0.569 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} 0.145 \\ -0.152 \\ 0 \end{bmatrix} \delta_c \quad (2)$$

3. SLIDING MODE CONTROLLER

Sliding mode control is part of the robust controller family. The importance of sliding mode controllers lies in: high precision, fast dynamic response, stability, simplicity of design and implementation, and robustness in the face of any variation of internal or external parameters [17], [18]. All these positive aspects of sliding mode control should not mask certain disadvantages [19]–[21]. The sliding mode controls proceed discontinuously, which leads to exciting all the frequencies of the system to be controlled, and therefore modes are not necessarily taken into account in modeling. Second, in most cases, the discontinuities of the control algorithm are managed directly on the actuators. If this organ is not designed for this type of oscillation, this risk leads to premature aging, and the system will be subjected at all times to a high control to ensure its convergence towards the desired state.

The principle of control by sliding modes is to force the trajectories of the system to reach a given surface, a sliding surface, and remain there until equilibrium. This command is done in two stages [22]–[24] the convergence towards the surface and then the sliding along with it. The SMC control law consists of two additive parts. That is:

$$u = u_{eq} + u_{glis} \quad (3)$$

with, u_{eq} : Nominal control, which is determined by the robot model, and u_{glis} : Sliding part, which is useful to compensate for model uncertainties. The synthesis of the sliding mode control is done in three stages:

- Choice of the sliding surface.
- Establish the convergence condition.
- To determine the law of control that makes it possible to reach the surface and remain there.

The sliding surface can be defined in the error state-space form as follows:

$$s(x) = [\alpha \quad \beta \quad \chi] \begin{bmatrix} \tilde{v} \\ \tilde{r} \\ \tilde{\psi} \end{bmatrix} = S * \tilde{x} = S * (x - x_d) \quad (4)$$

where α , β , and χ are the sliding surface constants.

The problem of following $x - x_d$ is the same as that of remaining on the surface $s(x)$ for all the time $t > 0$. Indeed $s(x) = 0$ represents an equation, whose unique solution is $(x - x_d) = 0$. In this way, the problem of following the desired vector x_d is reduced to keeping $s(x)$ as zero. The sliding surface $s(x)$ must obey the next condition: S is chosen so that $\lim_{x \rightarrow \infty} s(x) \rightarrow 0$ and $\lim_{x \rightarrow \infty} \dot{s}(x) \rightarrow 0$, assure the convergence of the error state space $\lim_{x \rightarrow \infty} \tilde{x} \rightarrow 0$. The Lyapunov candidate function $V(s) = \frac{1}{2} s(x)^2$, represents the decay of the energy's system, and guarantees that the system state converges to the sliding surface if the following sliding condition is respected [25], [26]:

$$\dot{V}(s) = s(x) \dot{s}(x) \leq -\eta |s(x)| \quad (5)$$

or,

$$\dot{s}(x) \leq -\eta^2 \text{sign}(s(x)) \quad (6)$$

differentiating the sliding surface (20), we obtain:

$$\dot{s}(x) = S^T \dot{\tilde{x}} = S^T (Ax + Bu - \dot{x}_d) \leq -\eta^2 \text{sign}(s(x)) \quad (7)$$

the sliding surface time derivative permits to express of the two parts of the control: u_{eq} , and u_{glis} , with:

$$u = -(S^T B)^{-1} S^T Ax - (S^T B)^{-1} S^T \dot{x}_d - (S^T B)^{-1} \eta^2 \text{sign}(s(x)) \quad (8)$$

then, the control to apply to the system is deduced:

$$u \leq u_{eq} + u_{glis} u_{eq} = -(S^T B)^{-1} S^T Ax - (S^T B)^{-1} S^T \dot{x}_d u_{glis} = -(S^T B)^{-1} \eta^2 \text{sign}(s(x)) \quad (9)$$

in our case, the desired states are constant values, so $\dot{x}_d = 0$. thus (9) becomes:

$$u_{eq} = -(S^T B)^{-1} S^T A x = -kx \quad (10) \quad u_{glis} = -(S^T B)^{-1} \eta^2 \text{sign}(s(x)) \quad (10)$$

finally, the sliding surface and the command are given by the expression:

$$\delta_c = (0.1052v + 0.0324r + 0.8693(\psi - \psi_d)) + 0.5\text{sign}(3v + 33r + 20(\psi - \psi_d)) \quad (11)$$

To reduce or eliminate the phenomenon of chattering, one will replace the term $\text{sign}(s(x))$ in the discontinuous part of the command with a softer variable term, like the hyperbolic tangent function $\tanh(s(x))$, this function has the advantage of varying the switching bandwidth [5], [10]. In the next section, we think of a new control method that guarantees all the advantages of the sliding mode controller and eliminates the chattering phenomenon. this is the Backstepping control, one of the more advanced commands.

4. BACKSTEPPING CONTROL

In recent years, much progress has been made in the field of controlling non-linear systems. The backstepping technique is one of these breakthroughs in this field. It proposes a systematic synthesis method intended for the class of nonlinear systems having a triangular shape. It is based on the decomposition of the entire control system, which is a generally multivariable and high order, into a cascade of first-order control subsystems [13], [14]. For each subsystem, a so-called virtual control law is calculated. The latter will serve as a reference for the next subsystem until the control law for the complete system is obtained. Moreover, this technique has the advantage of keeping the nonlinearities useful for the performance and the robustness of the command, unlike the linearization methods. The determination of the control laws that results from this approach is based on the use of Lyapunov control functions. Backstepping command principle of operation [27]-[38]:

- Definition of an error variable $e = x - x_d$.
- Definition of a Lyapunov function from this error $V(x) = \frac{1}{2} e^2$.
- Determination of a virtual control variable x_i .
- Continue until you find the final command u .

now we rewrite our system (2) in the triangular form, that is to say in the controllable companion form:

$$\dot{\psi} = r \quad \dot{r} = v \quad \dot{v} = -0.08625r - 0.778v + \delta_c \quad (12)$$

we apply the backstepping control to the model (12),
Step 1: we define the first variable of the error e_1 , such as:

$$e_1 = \psi - \psi_d \Rightarrow \dot{e}_1 = \dot{\psi} - \dot{\psi}_d = r - \dot{\psi}_d \quad (13)$$

We choose the first Lyapunov function V_1 , such that:

$$V_1 = \frac{1}{2} e_1^2 \Rightarrow \dot{V}_1 = e_1 \dot{e}_1 \quad (14)$$

for V_1 to be negative, it is necessary that:

$$\begin{aligned} \dot{V}_1 \leq -\alpha_1 e_1^2 \Rightarrow e_1 \dot{e}_1 \leq -\alpha_1 e_1^2 \Rightarrow \dot{e}_1 \leq -\alpha_1 e_1 \Rightarrow \\ r - \dot{\psi}_d \leq -\alpha_1 e_1 \quad r = -\alpha_1 e_1 + \dot{\psi}_d = -\alpha_1 \psi + \alpha_1 \psi_d + \dot{\psi}_d \end{aligned} \quad (15)$$

the virtual control calculated in the first step will be considered as a reference for the following step.
Step 2: we define the first variable of the error e_2 , such as:

$$e_2 = r - r_d = r + \alpha_1 \psi - \alpha_1 \psi_d - \dot{\psi}_d \Rightarrow \dot{e}_2 = \dot{r} - \dot{r}_d = v + \alpha_1 r - \alpha_1 \dot{\psi}_d - \ddot{\psi}_d \quad (16)$$

we choose the first Lyapunov function V_2 , such that:

$$V_2 = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 \Rightarrow \dot{V}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 \quad (17)$$

for V_2 to be negative, it is necessary that:

$$\begin{aligned} \dot{V}_2 \leq -\alpha_2 e_2^2 \quad e_2 \dot{e}_2 \leq -\alpha_2 e_2^2 \Rightarrow \dot{e}_2 \leq -\alpha_2 e_2 \Rightarrow v + \alpha_1 r - \alpha_1 \dot{\psi}_d - \ddot{\psi}_d \leq -\alpha_2 e_2 \quad v = \\ -\alpha_2 e_2 - \alpha_1 r + \alpha_1 \dot{\psi}_d + \ddot{\psi}_d = -(\alpha_2 + \alpha_1)r - \alpha_2 \alpha_1 \psi + \alpha_2 \alpha_1 \psi_d + (\alpha_2 + \alpha_1) \dot{\psi}_d + \ddot{\psi}_d \end{aligned} \quad (18)$$

the virtual control calculated in the second step will be considered as a reference for the following step
Step 3: we define the first variable of the error e_3 , such as:

$$e_3 = v - v_d = v + (\alpha_2 + \alpha_1)r + \alpha_2\alpha_1\psi - \alpha_2\alpha_1\psi_d - (\alpha_2 + \alpha_1)\dot{\psi}_d - \ddot{\psi}_d \quad (19)$$

its derivative is:

$$\begin{aligned} \dot{e}_3 = \dot{v} - \dot{v}_d = & (\alpha_2\alpha_1 - 0.08625)r + (\alpha_2 + \alpha_1 - 0.778)v + \delta_c \\ & - \alpha_2\alpha_1\dot{\psi}_d - (\alpha_2 + \alpha_1)\ddot{\psi}_d - \ddot{\psi}_d \end{aligned} \quad (20)$$

We choose the first Lyapunov function V_3 , such that:

$$V_3 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 \Rightarrow \dot{V}_3 = e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3 \quad (21)$$

for V_3 to be negative, it is necessary that:

$$\begin{aligned} \dot{V}_3 \leq -\alpha_3 e_3^2 \Rightarrow e_3 \dot{e}_3 \leq -\alpha_3 e_3^2 \Rightarrow \dot{e}_3 \leq -\alpha_3 e_3 \\ \Rightarrow \delta_c = -\alpha_3\alpha_2\alpha_1\psi - (\alpha_3\alpha_2 + \alpha_3\alpha_1 + \alpha_2\alpha_1 - 0.08625)r \\ - (\alpha_3 + \alpha_2 + \alpha_1 - 0.778)v + \alpha_3\alpha_2\alpha_1\psi_d + (\alpha_3\alpha_2 + \alpha_3\alpha_1 + \alpha_2\alpha_1)\dot{\psi}_d \\ + (\alpha_3 + \alpha_2 + \alpha_1)\ddot{\psi}_d + \ddot{\psi}_d \end{aligned} \quad (22)$$

finally, we find the numerical expression of the backstepping control:

$$\delta_c = -0.3750\psi - 1.5388r - 1.4720v + 0.3750\psi_d + 1.6250\dot{\psi}_d + 2.25\ddot{\psi}_d + \ddot{\psi}_d \quad (23)$$

5. SIMULATION RESULTS

In this section, we will present the results of the simulations of these two control laws, which we studied in the previous sections and are applied to the autonomous underwater robot system, to see what type of controllers will give us the advantage to improve the performance of the autonomous underwater robot. The objective of these simulation tests is to find a command which gives both better robustness in the face of parametric uncertainties and external disturbances and better convergence towards the desired trajectories of the autonomous underwater robot [10], [5]. The robot is considered to be on the surface, with zero initial conditions. The forward speed of the AUV is constant: $u = u_0 = 2.2 \text{ m/s}$

5.1. Noiseless simulation

We note that the robot follows its desired trajectory with precision in the two commands studied in the previous sections Figure 2(a). we also note that the yaw rate is zero each time the robot reaches its desired trajectory Figure 3(b). Indeed, as long as the desired yaw is not reached, the control surfaces are saturated Figure. 3(a). We notice in the graph of the Yaw control surfaces that the chattering phenomenon is eliminated with the Backstepping control if it is compared with the graph of the control surfaces simulated by the sliding mode command.

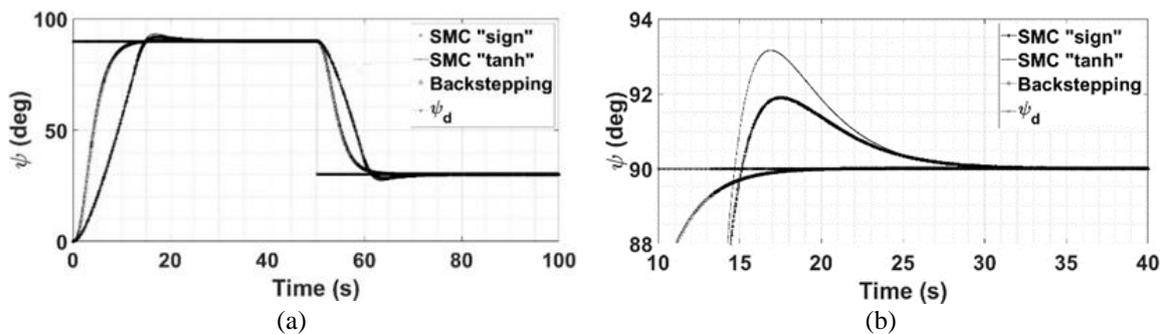


Figure 2. Heading control (a) heading control of the robot and (b) heading control zoom

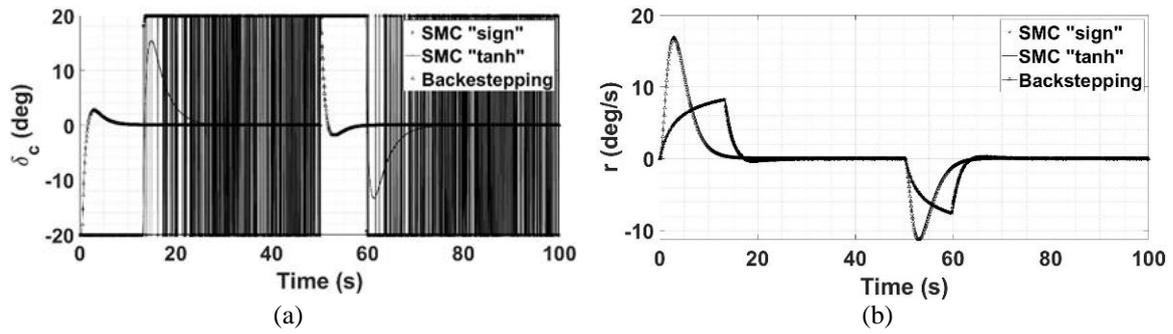


Figure 3. Rudder controls and yaw velocity (a) rudder controls the heading of the robot and (b) yaw velocity of the robot AUV

We also notice the saturation of the yaw control surfaces which works by the sliding mode command, either with the sign function or the hyperbolic tangent function, if it is compared with the graph of the control surfaces which works by the Backstepping command. we can conclude here that the backstepping command that the steering consumes less energy to reach and follow its trajectory, it is understood with the sliding mode command consumes more energy from the batteries in its operation. We note that the backstepping control is somewhat faster in converging towards the desired behavior with a small difference in the time to reach the desired path if compared to the sliding mode control Figure 2(b).

5.2. Simulation with noises

We are interested in this part, in the test of the robustness of the sliding mode control and the Backstepping control previously developed, where we will impose a drag force on the movement of the robot (on the input of the system, i.e. on the control surfaces) in the horizontal plane, i.e. we apply a disturbing force $p = 7 \sin(0.63t)$ at the instant $t = 30$ s. of course without forgetting that we will also add the parametric uncertainties of +20% to the hydrodynamic parameters. It can be seen that the robot follows its desired trajectory with precision, despite the presence of disturbing drag forces with the sliding mode control which uses the sign function as a saturation function Figure 4. On the other hand, the Backstepping control lost its precision during the presence of disturbing forces. we can say here that the sliding mode control has very good robustness in the rejection of disturbances. On the other hand, it can be seen from Table 1, that the Backstepping control always maintains its speed to achieve its desired trajectories. The robot is autonomous in its movement because it is charged with batteries and not connected to cables, which allows it to travel long distances, but these distances are determined by the battery and the time of its exhaustion. From this point of view, it is noticed from the simulation results that the yaw rudder controlled by Backstepping consumes less power, which ensures a good time for a long-distance segment before the battery runs out. This advantage is due to the absence of the chattering phenomenon in the design of the Backstepping control Figure 5.

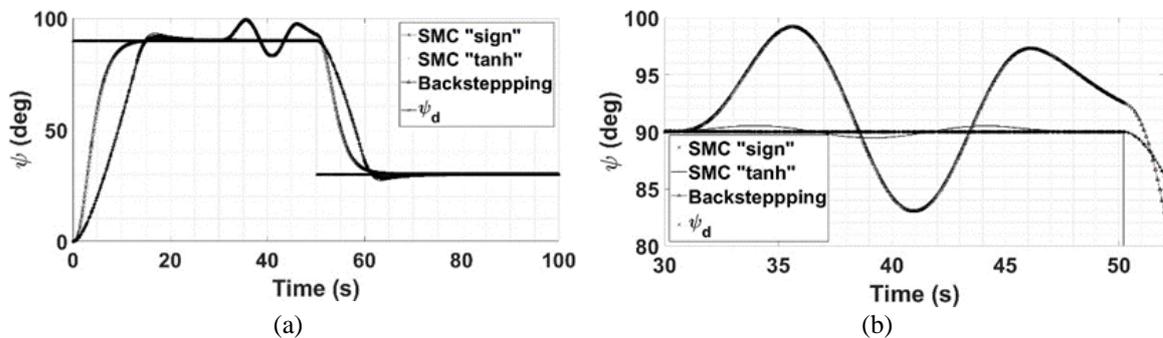


Figure 4. Heading control with disruptive drag force (a) AUV robot heading control with disruptive drag force and (b) AUV robot heading control zoom with disruptive drag force

Table 1. A comparative study with the two commands applied to robots with noise by drag forces

Control type	Error $\psi - \psi_d$	Energy consumption (W/s)	Convergence time towards the desired values (s)	Robustness
Sliding mode control with "sign" function	2.83e-03	400	30 s	Excellent
Sliding mode control with "tanh" function	1.01e-06	7.70e-13	30 s	Good
Backstepping control	5.53e-09	2.13e-20	18 s	Acceptable

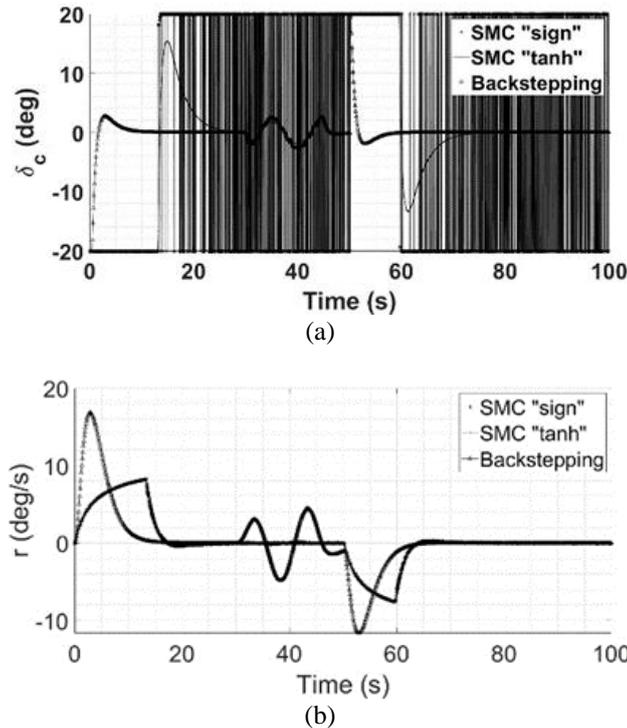


Figure 5. Rudder controls and Yaw velocity with disruptive drag force (a) Rudder controls the heading of the robot with disruptive drag force and (b) Yaw velocity of the robot AUV with disruptive drag force

6. CONCLUSION

Based on the dynamic model presented in section 2, we used several robust control techniques for heading control of an autonomous underwater robot with sliding mode and backstepping approaches. It can be noted that the control in sliding mode with the sign function consumes a lot of energy. Using the hyperbolic tangent function instead of the sign function in the sliding mode control greatly reduces the chattering effect. With the external noise added, we noticed the reappearance of the chattering effect in the control signal in sliding mode using the hyperbolic tangent function. The chattering effect is therefore not resolved. The implementation of the backstepping command of the autonomous underwater robot shows acceptable robustness in the face of external disturbances, but with such rapidity and precision in the convergence towards the desired heading.

Finally, the parametric uncertainties and the external noise are better rejected by the sliding mode control laws. on the other hand, we can conclude that the backstepping controllers improve the minimization of the energy consumption of the system. In general conclusion, we find that the control by a sliding mode which uses the hyperbolic tangent function is the most suitable control for our underwater robot because of its good robustness and the energy consumption of the battery which was acceptable. For future work: it would be interesting to be able to use new hybrid controls, to improve the precision and the speed in the convergence on the desired trajectories, such as the control by integral backstepping.

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