SLIDING MODE CONTROL OF AN UNDERWATER ROBOTIC VEHICLE INCLUDING ADAPTIVE FUZZY DEAD-ZONE COMPENSATION

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Abstract. *Due to the great technological improvement obtained in the last decades, it became possible to use robotic vehicles for underwater exploration. During the execution of a certain task with the robotic vehicle, the operator needs to monitor and control a number of parameters. If some of these parameters, as for instance the position and the orientation of the vehicle, could be controlled automatically, the teleoperation of the vehicle can be enormously facilitated. Based on experimental tests, it was verified that ROV's thruster system can exhibit dead-zone nonlinearities. This work describes the development of a variable structure control strategy for an underwater robotic vehicle with a thruster system subject to dead-zone input. Numerical results are presented in order to demonstrate the control system performance.*

Keywords: *Adaptive Algorithms, Dead zone, Fuzzy logic, Sliding Modes, Underwater Robotic Vehicles*

1. INTRODUCTION

The control system is one of the most important elements of an underwater robotic vehicle, and its characteristics (advantages and disadvantages) play an essential role when one has to choose a vehicle for a specific mission. Unfortunately, the problem of designing accurate positioning systems for underwater robotic vehicles still challenges many engineers and researchers interested in this particular branch of engineering science. A growing number of papers dedicated to the position and orientation control of such vehicles confirms the necessity of the development of a controller, that could deal with the inherent nonlinear system dynamics, imprecise hydrodynamic coefficients, and external disturbances.

It has already been shown (Yuh, 1994; Goheen and Jeffreys, 1990) that, in the case of underwater vehicles, the traditional control methodologies are not the most suitable choice and cannot guarantee the required tracking performance. On the other hand, sliding mode control, due to its robustness against modeling inaccuracies and external disturbance, has proven to be a very attractive approach to cope with this problems (Bessa et al., 2008c; Chatchanayuenyong and Parnichkun, 2007; Pisano and Usai, 2004; Guo et al., 2003; Kreuzer and Pinto, 1996; Christi et al., 1990; Healey and Lienard, 1985; Yoerger and Slotine, 1985). But a well known drawback of conventional sliding mode controllers is the chattering effect. To overcome the undesired effects of the control chattering, Slotine (1984) proposed the adoption of a thin boundary layer neighboring the switching surface, by replacing the sign function by a saturation function. This substitution can minimize or, when desired, even completely eliminate chattering, but turns *perfect tracking* into a *tracking with guaranteed precision* problem, which in fact means that a steady-state error will always remain. In order to enhance the tracking performance inside the boundary layer, some adaptive strategy should be used for uncertainty/disturbance compensation.

Due to the possibility to express human experience in an algorithmic manner, fuzzy logic has been largely employed in the last decades to both control and identification of dynamical systems. In spite of the simplicity of this heuristic approach, in some situations a more rigorous mathematical treatment of the problem is required. Recently, much effort (Liang and Su, 2003; Wong et al., 2001; Ha et al., 2001; Yu et al., 1998) has been made to combine fuzzy logic with sliding mode methodology. An appealing option is to embed an adaptive fuzzy inference system inside the boundary layer of a sliding mode controller, to cope with the uncertainties and disturbances that can arise (Bessa and Barrêto, 2009). This control strategy has already been successfully applied to the depth regulation of remotely operated underwater vehicles (Bessa et al., 2008c) and to chaos control in a nonlinear pendulum (Bessa et al., 2009a).

As demonstrated by (Bessa et al., 2004, 2005, 2006b), marine thrusters may also exhibit non-smooth nonlinearities such as dead-zones. Dead-zone is a hard nonlinearity, frequently encountered in many actuators of industrial control systems, especially those containing some very common components, such as hydraulic (Knohl and Unbehauen, 2000; Bessa et al., 2006a; Valdiero et al., 2006) or pneumatic (Guenther and Perondi, 2006; Andrighetto et al., 2008; Valdiero et al., 2008) valves.

Dead-zone characteristics are often unknown and it was already observed that its presence can severely reduce control system performance and lead to limit cycles in the closed-loop system. The growing number of papers involving systems with dead-zone input confirms the importance of taking such a hard nonlinearity into account during the control system design process. The most common approaches are adaptive schemes (Tao and Kokotović, 1994; Wang et al., 2004; Zhou et al., 2006; Ibrir et al., 2007), fuzzy systems (Kim et al., 1994; Oh and Park, 1998; Lewis et al., 1999; Bessa et al., 2008a), neural networks (Šelmić and Lewis, 2000; Tsai and Chuang, 2004; Zhang and Ge, 2007) and variable structure methods (Corradini and Orlando, 2002; Shyu et al., 2005). Many of these works (Tao and Kokotović, 1994; Kim et al., 1994; Oh and Park, 1998; Šelmić and Lewis, 2000; Tsai and Chuang, 2004; Zhou et al., 2006) use an inverse dead-zone to compensate the negative effects of the dead-zone nonlinearity even though this approach leads to a discontinuous control law and requires instantaneous switching, which in practice can not be accomplished with mechanical actuators. An alternative scheme, without using the dead-zone inverse, was originally proposed by Lewis et al. (1999) and also adopted by Wang et al. (2004). In both works, the dead-zone is treated as a combination of a linear and a saturation function. This approach was further extended by Bessa et al. (2008b), in order to accommodate non-symmetric dead-zones. The control strategy proposed by Bessa et al. (2008b) has also already been successfully applied to electro-hydraulic systems (Bessa et al., 2009b).

In this paper, based on the control scheme proposed in (Bessa et al., 2008b), an adaptive fuzzy sliding mode controller is employed for the dynamic positioning of an underwater vehicle with four controllable degrees of freedom and considering thruster system subject to a dead-zone input. The adoption of a reduced order mathematical model and the development of the control system in a decentralized fashion, neglecting cross-coupling terms, is discussed. Numerical results are also provided to confirm the control system efficacy.

2. VEHICLE DYNAMICS

A reasonable model to describe the underwater vehicle's dynamical behavior must include the rigid-body dynamics of the vehicle's body and a representation of the surrounding fluid dynamics. Such a model must be composed of a system of ordinary differential equations, to represent rigid-body dynamics, and partial differential equations to represent both tether and fluid dynamics.

In order to overcome the computational problem of solving a system with this degree of complexity, in the majority of publications (Bessa et al., 2008c; Antonelli, 2007; Hoang and Kreuzer, 2007; Smallwood and Whitcomb, 2004; Hsu et al., 2000b,a; Kiriazov et al., 1997; Yoerger and Slotine, 1985) a lumped-parameters approach is employed to approximate vehicle's dynamical behavior.

The equations of motion for underwater vehicles can be presented with respect to an inertial reference frame or with respect to a body-fixed reference frame, Fig. 1. On this basis, the equations of motion for underwater vehicles can be expressed, with respect to the body-fixed reference frame, in the following vectorial form:

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{k}(\boldsymbol{\nu}) + \mathbf{h}(\boldsymbol{\nu}) + \mathbf{g}(\mathbf{x}) + \mathbf{d} = \boldsymbol{\tau} \quad (1)$$

where $\boldsymbol{\nu} = [\upsilon_x, \upsilon_y, \upsilon_z, \omega_x, \omega_y, \omega_z]$ is the vector of linear and angular velocities in the body-fixed reference frame, $\mathbf{x} = [x, y, z, \alpha, \beta, \gamma]$ represents the position and orientation with respect to the inertial reference frame, $\mathbf{M}$ is the inertia matrix, which accounts not only for the rigid-body inertia but also for the so-called hydrodynamic added inertia, $\mathbf{k}(\boldsymbol{\nu})$ is the vector of generalized Coriolis and centrifugal forces, $\mathbf{h}(\boldsymbol{\nu})$ represents the hydrodynamic quadratic damping, $\mathbf{g}(\mathbf{x})$ is the vector of generalized restoring forces (gravity and buoyancy), $\mathbf{d}$ stands for occasional disturbances, and $\boldsymbol{\tau}$ is the vector of control forces and moments.

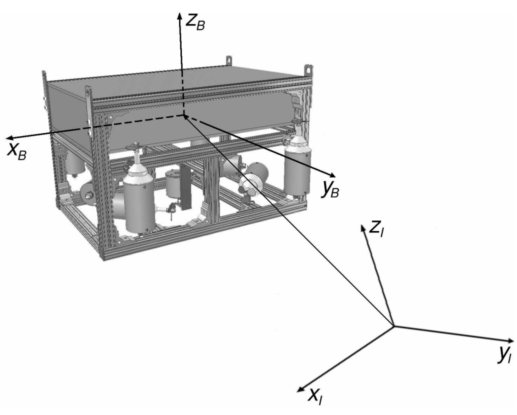

Figure 1. Underwater vehicle with both inertial and body-fixed reference frames.

It should be noted that in the case of remotely operated underwater vehicles (ROVs), the metacentric height is sufficiently large to provide the self-stabilization of roll (α) and pitch (β) angles. This particular constructive aspect also allows the order of the dynamic model to be reduced to four degrees of freedom, $\mathbf{x} = [x,\, y,\, z, \gamma]$, and the vertical motion (heave) to be decoupled from the motion in the horizontal plane. This simplification can be found in the majority of works presented in the specialized literature (Hoang and Kreuzer, 2007; Zanoli and Conte, 2003; Guo et al., 2003; Hsu et al., 2000b; Kiriazov et al., 1997; Pinto, 1996; Da Cunha et al., 1995; Yoerger and Slotine, 1985). Thus, the positioning system of a ROV can be divided in two different parts: Depth control (concerning variable z), and control in the horizontal plane (variables x, y and γ).

Another important issue in the case of ROVs is the disturbance force caused by the umbilical (or tether cable). The umbilical can be treated as a continuum, discretized with the finite element method or modeled as multibody system (Bevilacqua et al., 1991; Pinto, 1996). However, the adoption of any of these approaches requires a computational effort that would be prohibitive for on-line estimation of the control action. A common way to surmount this limitation is to consider the forces and moments exerted by the tether as random, and incorporate them into the vector $\mathbf{d}$.

Regarding the thrust forces, the steady-state axial thrust T produced by marine thrusters is presented in the literature as proportional to the square of propeller's angular velocity Ω (Newman, 1986). This quadratic relationship can be conveniently represented by

$$T = C_T\, \Omega|\Omega| \tag{2}$$

where C_T is a function of the advance ratio and depends on constructive characteristics of each thruster.

Nevertheless, according to experimental results (Bessa et al., 2004, 2005, 2006b), marine thrusters may exhibit dead-zones and could be mathematically described by

$$T = D(\Omega|\Omega|) = \begin{cases} m_l\,(\Omega|\Omega| - \delta_l) & \text{if} \quad \Omega|\Omega| \leq \delta_l \\ 0 & \text{if} \quad \delta_l < \Omega|\Omega| < \delta_r \\ m_r\,(\Omega|\Omega| - \delta_r) & \text{if} \quad \Omega|\Omega| \geq \delta_r \end{cases} \tag{3}$$

Figure 2 shows a comparative analysis between some experimental results and the thrust models presented in Eq.(2) and Eq.(3). The required parameters for both models were obtained with an implementation of Levenberg-Marquardt's algorithm (Marquardt, 1963).

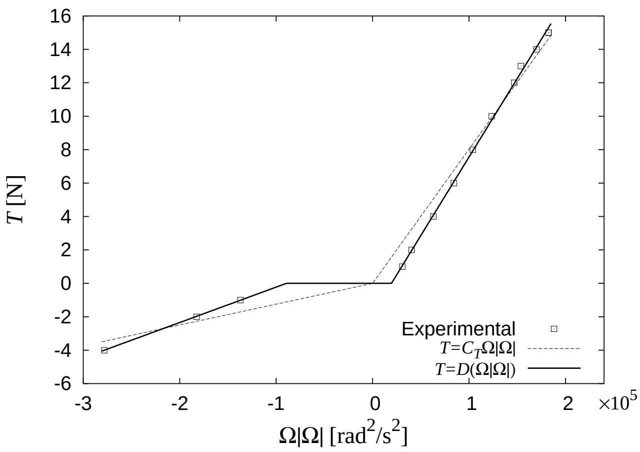

Figure 2. Comparative analysis between experimental data and two thrust models.

The experiments were carried out in a wave channel with the thruster units of a small remotely operated underwater vehicle, developed at the Institute of Mechanics and Ocean Engineering of the Hamburg University of Technology. The ROV is equipped with eight thrusters for dynamic positioning with respect to four degrees of freedom and a passive arm for position and attitude measurement. A picture of the experimental underwater vehicle is presented in Fig. 3.

For control purposes, Eq. (3) can be rewritten in a more appropriate form (Bessa et al., 2008b):

$$T = D(\Omega|\Omega|) = m(\Omega|\Omega|)[\Omega|\Omega| - d(\Omega|\Omega|)] \tag{4}$$

where

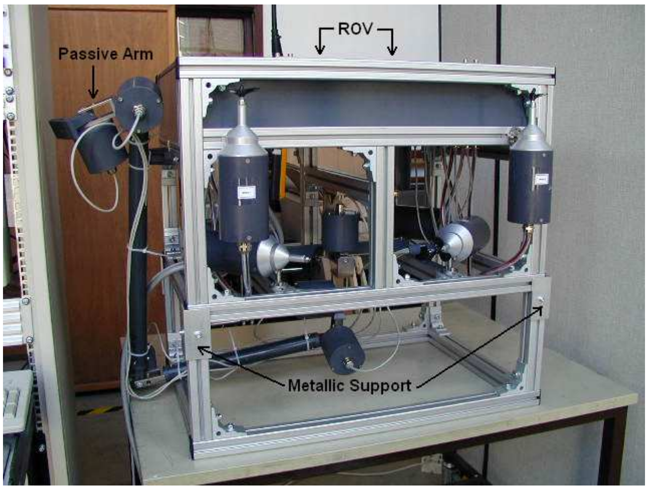

Figure 3. The experimental remotely operated underwater vehicle.

$$m(\Omega|\Omega|) = \begin{cases} m_l & \text{if} \quad \Omega|\Omega| \le 0 \\ m_r & \text{if} \quad \Omega|\Omega| > 0 \end{cases} \tag{5}$$

and

$$d(\Omega|\Omega|) = \begin{cases} \delta_l & \text{if} \quad \Omega|\Omega| \le \delta_l \\ \Omega|\Omega| & \text{if} \quad \delta_l < \Omega|\Omega| < \delta_r \\ \delta_r & \text{if} \quad \Omega|\Omega| \ge \delta_r \end{cases} \tag{6}$$

Furthermore, the effect of the forces produced by each one of the eight thrusters on the vehicle can be described in body-fixed reference frame by

$$\boldsymbol{\tau} = \mathbf{BT} \tag{7}$$

where $\mathbf{T} \in \mathbb{R}^8$ is a vector containing the forces produced by each thruster and $\mathbf{B} \in \mathbb{R}^{4\times8}$ is a matrix which represents the distribution of the thrust forces on the vehicle.

3. DYNAMIC POSITIONING SYSTEM

The dynamic positioning of underwater robotic vehicles is essentially a multivariable control problem. Nevertheless, as demonstrated by Slotine (Slotine, 1983), the variable structure control methodology allows different controllers to be separately designed for each degree of freedom. Over the past decades, decentralized control strategies have been successfully applied to the dynamic positioning of underwater vehicles (Chatchanayuenyong and Parnichkun, 2007; Smallwood and Whitcomb, 2004; Kiriazov et al., 1997; Da Cunha et al., 1995; Yoerger and Slotine, 1985).

The control law for each degree of freedom can be easily designed with respect to the inertial reference frame, Eq. (1) should be rewritten in this coordinate system. On this basis, considering that the restoring forces could be passively compensated (Kiriazov et al., 1997) and that $\dot{\mathbf{x}} = \mathbf{J}(\mathbf{x})\boldsymbol{\nu}$, $\boldsymbol{\nu} = \mathbf{J}^{-1}(\mathbf{x})\dot{\mathbf{x}}$ and $\dot{\boldsymbol{\nu}} = \dot{\mathbf{J}}^{-1}\dot{\mathbf{x}} + \mathbf{J}^{-1}\ddot{\mathbf{x}}$, where $\mathbf{J}(\mathbf{x})$ is the Jacobian transformation matrix, the equations of motion of an underwater vehicle, with respect to the inertial reference frame, becomes

$$\bar{\mathbf{M}}\ddot{\mathbf{x}} + \bar{\mathbf{k}} + \bar{\mathbf{h}} + \bar{\mathbf{d}} = \bar{\boldsymbol{\tau}} \tag{8}$$

where $\bar{\mathbf{M}} = \mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$, $\bar{\mathbf{k}} = \mathbf{J}^{-\mathrm{T}}\mathbf{k} + \mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\dot{\mathbf{J}}^{-1}\dot{\mathbf{x}}$, $\bar{\mathbf{h}} = \mathbf{J}^{-\mathrm{T}}\mathbf{h}$, $\bar{\mathbf{d}} = \mathbf{J}^{-\mathrm{T}}\mathbf{d}$ and $\bar{\boldsymbol{\tau}} = \mathbf{J}^{-\mathrm{T}}\boldsymbol{\tau}$.

In order to develop the control law with a decentralized approach, Eq. (8) can be rewritten as follows:

$$\ddot{x}_i = \bar{m}_i^{-1}(\bar{\tau}_i - \bar{k}_i - \bar{h}_i - \bar{d}_i); \quad i = 1, 2, 3, 4, \tag{9}$$

where x_i, $\bar{\tau}_i$, $\bar{k}_i$, $\bar{h}_i$ and $\bar{d}_i$ are the components of $\mathbf{x} = [x, y, z, \gamma]$, $\bar{\boldsymbol{\tau}}$, $\bar{\mathbf{k}}$, $\bar{\mathbf{h}}$ and $\bar{\mathbf{d}}$, respectively. Concerning $\bar{m}_i$, it represents the main diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$. The off-diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$ are incorporated in the vector $\bar{\mathbf{p}}$.

In this way, according to (Bessa et al., 2008b) and considering the saturation function as the smooth approximation to the ideal relay, and $s_i = \dot{\tilde{x}}_i + \lambda_i \tilde{x}_i$, the control law for each degree of freedom could stated as follows

$$\bar{\tau}_i = \hat{\bar{k}}_i + \hat{\bar{h}}_i + \hat{\bar{d}}_i + \hat{\bar{m}}_i \left(\ddot{x}_{d_i} - \lambda_i \dot{\tilde{x}}_i \right) - K_i \, \mathrm{sat}(s_i/\phi_i) \tag{10}$$

where $\hat{\bar{m}}_i$, $\hat{\bar{k}}_i$ and $\hat{\bar{h}}_i$ stands for estimates of $\bar{m}_i$, $\bar{k}_i$ and $\bar{h}_i$, respectively.

Concerning $\hat{\bar{m}}_i$, it represents in the depth controller the mass of the vehicle plus the respective added mass. In the horizontal plane, estimates of the main diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$, may be attributed to the correspondent $\hat{\bar{m}}_i$. To ensure the stability of the closed-loop system, estimates of the off-diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$ should be incorporated in the vector $\bar{\mathbf{d}}$, as will be discussed further in the paper.

It should be emphasized that the lumped parameters approach, adopted to describe the hydrodynamic effects (quadratic damping and added inertia), represents a simplification, and hence only estimates of the actual phenomena are available. Due to the presence of the term $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\dot{\mathbf{J}}^{-1}\dot{\mathbf{x}}$, the vector $\bar{\mathbf{k}}$ cannot be exactly known.

The gain K_i of each controller should be carefully determined in order to ensure the global stability of the closed-loop system, and robustness with respect to disturbances and uncertainties. According to (Bessa et al., 2008b), K_i must be defined as follows:

$$K_i \geq \mathcal{P}_i + \hat{\bar{m}}_i \mathcal{G}_i \eta_i + |\hat{d}_i(s_i)| + \hat{\bar{m}}_i (\mathcal{G}_i - 1) |\ddot{x}_{di} - \lambda_i \dot{\tilde{x}}_i| \tag{11}$$

where η_i are strictly positive constants related to the reaching time of each controller.

Defining $\hat{\bar{m}}_i = \sqrt{\bar{m}_{\max}\bar{m}_{\min}}$ and $\mathcal{G}_i = \sqrt{\bar{m}_{\max}/\bar{m}_{\min}}$ automatically implies that

$$\mathcal{G}_i^{-1} \leq \frac{\hat{\bar{m}}_i}{\bar{m}\ _i} \leq \mathcal{G}_i \tag{12}$$

Regarding $\mathcal{P}_i$, this term should be defined for each controller in order to compensate the uncertainties of the respective components of vectors $\bar{\mathbf{k}}$ and $\bar{\mathbf{h}}$, and perturbations provided by $\bar{\mathbf{p}}$, *i.e.*,

$$\left| \Delta \bar{k}_i + \Delta \bar{h}_i + \bar{d}_i \right| \leq \mathcal{P}_i \tag{13}$$

Returning to the control law, Eq. (10), the adoption of a saturation function, $\mathrm{sat}(\cdot)$, instead of the well-known sign function, $\mathrm{sgn}(\cdot)$, leads to the formation of a thin boundary layer neighboring each switching surface $S_i(t)$. The incorporation of this boundary layer can minimize or, when desired, even completely eliminate chattering, but turns *perfect tracking* into a *tracking with guaranteed precision* problem, leading to an inferior tracking performance.

In order to enhance the tracking performance, in this work, an adaptive fuzzy inference system is embedded inside the boundary layer, to cope with the uncertainties and disturbances that can arise.

The adopted fuzzy inference system was the zero order TSK (Takagi–Sugeno–Kang), whose rules can be stated in a linguistic manner as follows:

If $\hat{u}$ *is* $\hat{U}_r$ *then* $\hat{d} = \hat{D}_r$, $\quad r = 1, 2, \ldots, N$

where $\hat{U}_r$ are fuzzy sets, whose membership functions could be properly chosen, and $\hat{D}_r$ is the output value of each one of the R fuzzy rules.

Considering that each rule defines a numerical value as output $\hat{D}_r$, the final output $\hat{d}$ can be computed by a weighted average:

$$\hat{d}(s) = \frac{\sum_{r=1}^{R} w_r \cdot \hat{d}_r}{\sum_{r=1}^{R} w_r} \tag{14}$$

or, similarly, but now for every degree of freedom,

$$\hat{d}_i(s) = \hat{\mathbf{D}}_i^{\mathrm{T}} \mathbf{\Psi}_i(s_i) \tag{15}$$

where, $\hat{\mathbf{D}} = [\hat{D}_1, \hat{D}_2, \ldots, \hat{D}_N]^{\mathrm{T}}$ is the vector containing the attributed values $\hat{D}_r$ to each rule r, $\mathbf{\Psi}(s) = [\psi_1(s), \psi_2(s), \ldots, \psi_N(s)]^{\mathrm{T}}$ is a vector with components $\psi_r(s) = w_r / \sum_{r=1}^{N} w_r$ and w_r is the firing strength of each rule.

In order to obtain the most suitable values for $\hat{d}_i(s)$, the vectors of adjustable parameters will be automatically updated by the following adaptation law:

$$\dot{\hat{\mathbf{D}}}_i = -\varphi_i \, s_i \, \mathbf{\Psi}_i(s_i) \tag{16}$$

where φ_i are strictly positive constants related to the adaptation rate.

For a more detailed discussion about the stability and convergence properties of the proposed control law, the reader is referred to (Bessa and Barrêto, 2009) and (Bessa et al., 2008b).

Now, given the required control force $\bar{\boldsymbol{\tau}}$ and the thruster's arrangement on the vehicle, the force that should be produced by every thruster can be determined by

$$\mathbf{T} = \mathbf{B}^{\mathrm{T}}(\mathbf{B}\mathbf{B}^{\mathrm{T}})^{-1}\mathbf{J}^{-1}\bar{\boldsymbol{\tau}}$$

where $\mathbf{B}^{\mathrm{T}}(\mathbf{B}\mathbf{B}^{\mathrm{T}})^{-1}$ is the pseudo-inverse of matrix $\mathbf{B}$. In this way, considering the required thrust forces and Eq. (7), the related angular velocity could be easily estimated for each propeller.

4. SIMULATION RESULTS

The numerical simulations were performed with an implementation in C, with sampling rates of 500 Hz for control system and 1 kHz for dynamic model. The differential equations of the dynamic model were numerically solved with the fourth order Runge-Kutta method.

In order to simplify the design process, some parameters of the controller were chosen identical for all degrees of freedom, $\lambda_i = 0.6$, $\phi_i = 0.05$ and $\varphi_i = 1 \times 10^3$. Concerning the fuzzy system, the same triangular and trapezoidal membership functions, with the central values defined as $C_i = \{-3\ ;\ -1\ ;\ -0{,}5\ ;\ 0\ ;\ 0{,}5\ ;\ 1\ ;\ 3\}$, were adopted for each DOF. The vectors of adjustable parameters were initialized to zero, $\hat{\mathbf{D}}_i = \mathbf{0}$, and automatically updated according to Eq. (16). For the dynamic model, the following values were adopted: $\mathbf{M} = \mathrm{diag}\,\{80\,\mathrm{kg},\ 80\,\mathrm{kg},\ 100\,\mathrm{kg},\ 8\,\mathrm{kg\,m^2}\}$ and $\mathbf{h} = [125\,\upsilon_x|\upsilon_x|,\ 175\,\upsilon_y|\upsilon_y|,\ 250\,\upsilon_z|\upsilon_z|,\ 12{,}5\,\omega_z|\omega_z|]^{\mathrm{T}}$. The disturbance force was chosen to vary randomly in the range of ± 3 N. The random nature of the disturbance was simulated using the functions `rand()` and `srand()` of the C Standard Library. For controller design, the vehicle's parameters were chosen based on the assumption that exact values are not known, but with a maximal uncertainty of $\pm 25\%$.

To evaluate the control system performance, two different numerical simulations were performed. In the first case, the underwater robotic vehicle was intended to move only in the XY plane, from his initial position/orientation at rest, $\mathbf{x}_0 = [0,0,0,0]^{\mathrm{T}}$, to the desired final position/orientation $\mathbf{x_d} = [2.5\ ,\ 2\ ,\ 0\ ,\ \pi/2]^{\mathrm{T}}$. Once this final position/orientation is reached, it should stay there indefinitely, besides the disturbance forces. The obtained results are presented in Fig. 4.

Figure 4 shows the obtained response in the time domain. These results confirm that the proposed control strategy was able to regulate and stabilize the dynamical behavior of the underwater vehicle in the horizontal plane. As observed in Fig. 4(b), Fig. 4(d) and Fig. 4(f), the adaptive fuzzy sliding mode controller was also efficient in minimizing the undesirable chattering effect.

Finally, the second case was a trajectory tracking in $\mathbb{R}^3$. Here, from the initial position $\mathbf{x}_0 = [0,0,0,0]^{\mathrm{T}}$ at rest, the vehicle was forced to move to the following desired positions: $\mathbf{x}_1 = [0,3,3,0]^{\mathrm{T}}$, $\mathbf{x}_2 = [3,3,3,0]^{\mathrm{T}}$, $\mathbf{x}_3 = [3,3,0,0]^{\mathrm{T}}$, $\mathbf{x}_4 = [1,3,0,0]^{\mathrm{T}}$ and $\mathbf{x}_5 = [1,1,0,0]^{\mathrm{T}}$, where $t_0 = 0$ s, $t_1 = 30$ s, $t_2 = 60$ s, $t_3 = 90$ s, $t_4 = 120$ s, $t_5 = 150$ s. During the entire path, the yaw angle should be kept constant, $\gamma = 0$. The obtained results are presented in Fig. 5 and Fig. 6. By observing both figures, it can be verified that, with the proposed control system, the vehicle could follow the desired trajectory, in spite of the disturbance forces. It can be also observed, Fig. (6(d)), that the yaw angle (γ) was held within the acceptable bounds, defined by the chosen width of the boundary layer, $\phi_\gamma = 0.05$.

5. CONCLUDING REMARKS

In this paper, the problem of compensating uncertainty/disturbance in the dynamic positioning system of underwater robotic vehicles is considered. An adaptive fuzzy sliding mode controller is implemented to deal with the stabilization and trajectory tracking problems. The adoption of a reduced order mathematical model for the underwater vehicle and the development of a control system in a decentralized fashion, neglecting cross-coupling terms, is discussed. By means of numerical simulations, it could be verified that the proposed strategy is able to cope with the uncertainties in hydrodynamics coefficients, the dead-zone input and the disturbances, that can typically arise in the subaquatic environment.

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7. RESPONSIBILITY NOTICE

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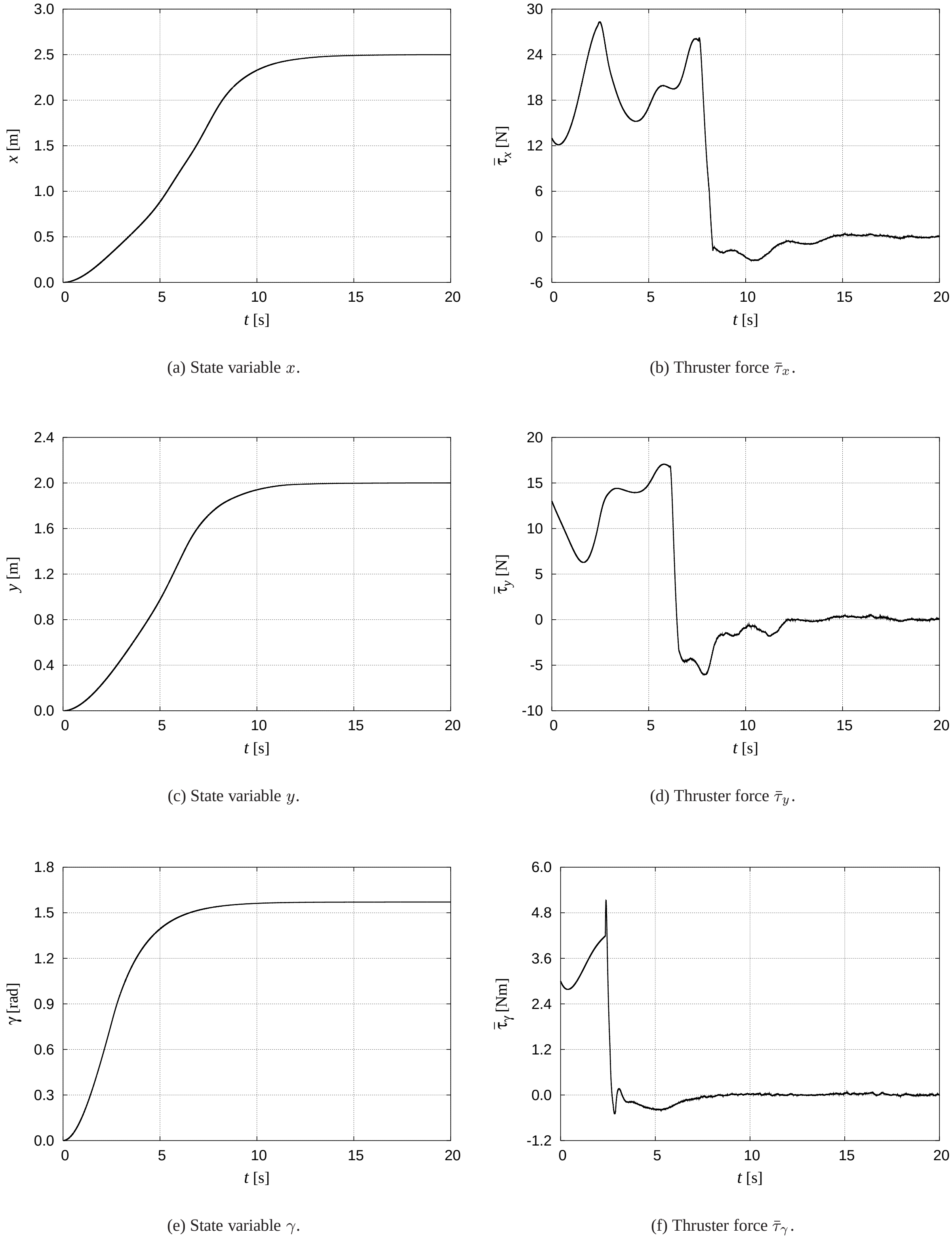


(a) State variable x.

(b) Thruster force $\bar{\tau}_x$.

(c) State variable y.

(d) Thruster force $\bar{\tau}_y$.

(e) State variable γ.

(f) Thruster force $\bar{\tau}_\gamma$.

Figure 4. Dynamic positioning of the vehicle in the horizontal plane.

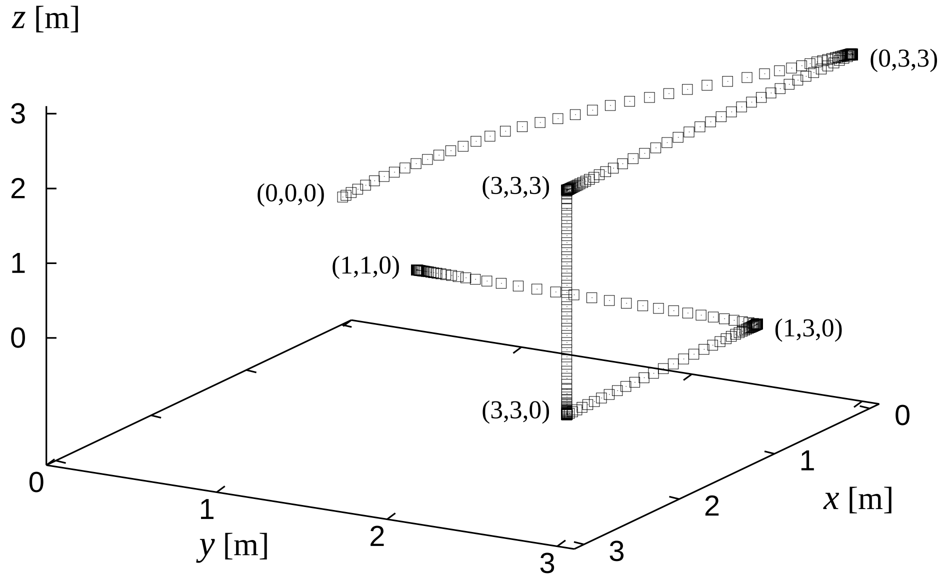
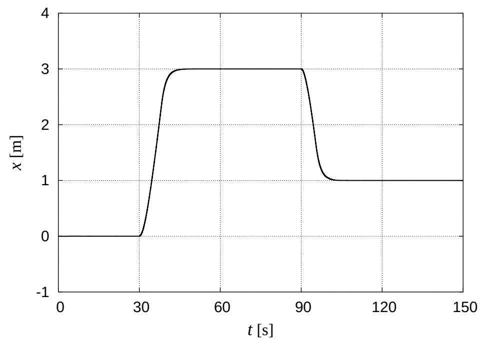
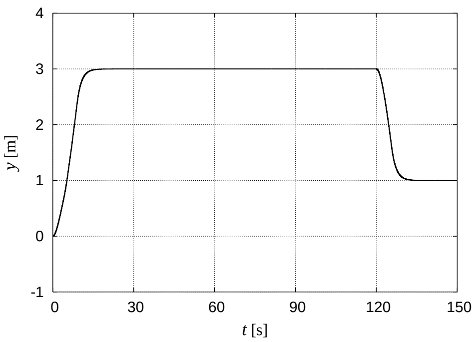


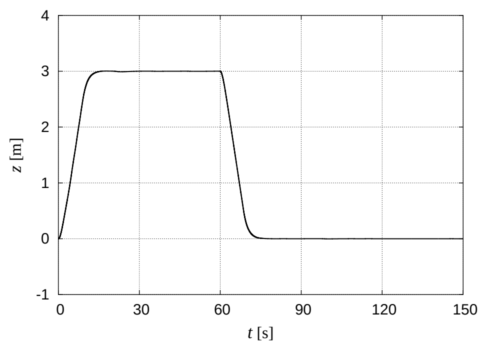
Figure 5. Dynamic positioning of the vehicle in $\mathbb{R}^3$



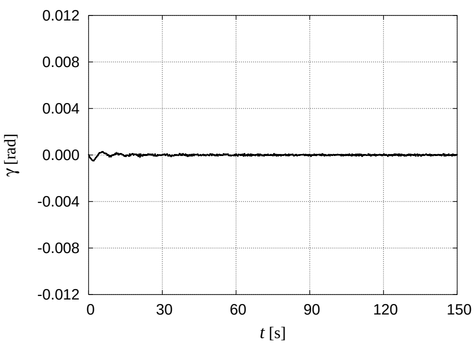
(a) State variable x.



(b) State variable y.



(c) State variable z.



(d) State variable γ.

Figure 6. State variables in the time domain, associated to the dynamic positioning in $\mathbb{R}^3$