Saturation based nonlinear depth and yaw control of underwater vehicles with stability analysis and real-time experiments

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This paper deals with two nonlinear controllers based on saturation functions with varying parameters, for set-point regulation and trajectory tracking on an Underwater Vehicle. The proposed controllers combine the advantages of robust control and easy tuning in real applications. The stability of the closed-loop system with the proposed nonlinear controllers is proven by Lyapunov arguments. Experimental results for the trajectory tracking control in 2 degrees of freedom, these are the depth and yaw motion of an underwater vehicle, show the performance of the proposed control strategy.

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1. Introduction

Underwater vehicles are more and more used for various types of applications, such as inspection, exploration, oceanography, biology, to name a few. They can be classified in two classes: the Autonomous Underwater Vehicles (AUVs) and the Remotely Operated Vehicles (ROVs). One of the main challenges for these types of vehicles lies in the design of the control strategy, given the nonlinear dynamics and the difficulty to accurately identify their hydrodynamic parameters [2–4]. The controller is used either to fully control the vehicle (for AUVs), or to assist the pilot (for ROVs) by providing features such as auto-depth, auto-altitude (with respect to the seabed), or auto-heading. Although many types of controllers have been studied during last decades, most of commercial underwater vehicles use PID controllers. For instance, PID control and acceleration feedback can be found in [5]; in [7] a PD controller considering the time-delay produced by the sensor has been proposed for an underwater vehicle. Nevertheless the drawback of these controllers is that they do not have a good performance when the parameters of the system change.

In practical applications, we can notice that a standard PID control design can be improved by bounding its signal. Consequently, several nonlinear PID controllers with bounded signal have been proposed in order to improve the performance of the closed-loop system. For instance, in [8] and [9] a nonlinear PD controller has been proposed for robot manipulators, where the constant proportional and derivative gains have been replaced with nonlinear functions. In [10] a nonlinear PID controller is proposed for a superconducting magnetic energy storage, where the idea was to improve the stability of the power system in a relatively wide operation range. In [11] a nonlinear PID controller was applied to a class of truck ABS (Anti-lock Brake System), where it has been shown that the nonlinear PID controller has better performance than the conventional PID controller.

In the literature there are some works about control strategies for AUVs, for example in the paper [12] the authors present a trajectory tracking control using a linear system to implement a sliding mode controller. In this case the unmodeled dynamics are considered as external perturbations. In [13] the simulation of a backstepping controller for robust diving against pitch perturbations is given. The reference [14] describes a classical algorithm of sliding mode, where the vehicle has a input/output decentralized dynamics; the main problem of this technic is the chattering. In [16] a nonlinear adaptive controller is proposed for depth and pitch control of a small underwater vehicle. The paper [17] presents a trajectory tracking control using Lagrange’s operators, allowing propose a novel path-following controller for UUVs. Concerning robust controllers, one possibility is to try to reduce undesirable dynamic couplings, for instance dynamic pitch and yaw coupling suppres-

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Finally, vehicle and in order to reduce further analysis, we assume that the vehicle is moving at low speeds, leading to a slightly simplified dynamics.

2.1. Prototype description

The L2ROV (Figs. 1 and 2) is a tethered underwater vehicle, whose size is about 75 cm long, 55 cm width, and 45 cm height. The propulsion system of this underwater vehicle consists of six thrusters, as illustrated in Fig. 2. According to the SNAME notation [19], the translational motions are referred to as surge, sway, and heave; while the rotational motions are roll, pitch, and yaw. The surge motion is generated by the sum of the forces created by T4 and T5, sway movement is actuated by T6, and heave is produced by the sum of thrusts of T1, T2, and T3. The roll movement is actuated through differential force of the thrusters T2 and T3; the pitch motion is obtained similarly using thrusters T1, T2, and T3, and the yaw motion is generated by T4 and T5. The experimental platform consists of a ROV driven by a laptop computer, with CPU Intel Core i7-3520 M 2.9 GHz, 8 GB RAM memory. The computer runs under Windows 7 operating system and the control software is developed with Visual C++ 2010. The computer receives the data from the ROV’s sensors (pressure, attitude), computes the control laws and sends input signals to the actuators. These latter are controlled by MD03 Motor Drives. The main features of this vehicle are described in Table 1.

2.2. Dynamic modeling

The dynamics of the vehicle, in the body-fixed-frame \((x_b, y_b, z_b)\) (more details see Fig. 3), can be expressed in a compact matrix form as [20]:

\[
M \ddot{v} + C(v) \dot{v} + D(v) \dot{v} + g(\eta) = \tau + w_e
\]  

(1)

\[
\dot{\eta} = J(\eta) \nu
\]  

(2)

where \(M \in \mathbb{R}^{6 \times 6}\) is the inertia matrix, \(C(v) \in \mathbb{R}^{6 \times 6}\) defines the Coriolis-centripetal matrix. In our case we assume that the vehicle is moving at low speeds, then this Coriolis matrix can be neglected. \(D(v) \in \mathbb{R}^{6 \times 6}\) represents the damping matrix, \(g(\eta) \in \mathbb{R}^{6 \times 1}\) describes the vector of restoring forces and moments, \(\tau = (T_1, T_2)^T = ((f_x, f_y, f_z), (c_x, c_y, c_z))^T \in \mathbb{R}^{6 \times 1}\) defines the vector of control inputs; \(w_e \in \mathbb{R}^{6 \times 1}\) defines the vector of disturbances; \(v = \)
\[ (v_1, v_2)^T = ((u, v, w), (p, q, r))^T \in \mathbb{R}^{6 \times 1} \] represents the linear and angular velocity vector in the body-fixed-frame; \( \eta = (\eta_1, \eta_2)^T = ((x, y, z), (\phi, \theta, \psi))^T \in \mathbb{R}^{6 \times 1} \) is the position and attitude vector decomposed in the earth-fixed-frame, and \( J(\eta) \in \mathbb{R}^{6 \times 6} \) is the transformation matrix mapping from the body-fixed-frame to earth-fixed-frame (see Fig. 3). For more details about the dynamic modeling, the reader can refer to [21,22].

2.2.1. Inertia and damping matrices

The inertia matrix \( M \) is the sum of the rigid-body inertia \( M_{RB} \) and the inertia of the added mass \( M_A \), as follows:

\[ M = M_{RB} + M_A \]  

In our case, we assume that the vehicle is moving at slow speeds; hence, the \( M \) matrix can be approximated by:

\[ M = \text{diag}(m - X_u, m - Y_v, m - Z_w, I_{xx} - K_p, I_{yy} - M_q, I_{zz} - N_r) \]  

where \( m \) is the mass of the vehicle, \( X_u, Y_v, Z_w, K_p, M_q, N_r \) represent hydrodynamic added mass, and \( I_{xx}, I_{yy}, I_{zz} \) are the moments of inertia of the rigid-body. L2ROV inertia parameters (computed from the ROV's 3D model), then we have obtained the following values in kg.m^2:

\[ I = \begin{bmatrix} 0.35 & -0.02 & -0.04 \\ -0.02 & 0.69 & -0.02 \\ -0.04 & -0.02 & 0.65 \end{bmatrix} \]  

Concerning the hydrodynamic damping, we consider the damping model for low-speed underwater vehicles. Thus we have:

\[ D(\nu) = \text{diag}([X_u, Y_v, Z_w, K_p, M_q, N_r]) \]  

For the L2ROV prototype the damping parameters included in the damping matrix have been experimentally estimated by applying the following procedure. First, the buoyancy of the ROV is adjusted to exactly compensate for the weight, so that the floatability is neutral. Then, a known force is applied to the ROV along the z axis. This force is produced by the thrusters and is known thanks to a previous calibration. As the vehicle submerges, the value of \( z \) is recorded (thanks to the depth sensor). Then, the speed along \( z \) is computed. After few seconds, the ROV reaches a steady state limit speed. The value of \( Z_w \), the damping parameter along \( z \), is approximated by:

\[ Z_w \approx \frac{f_z}{w_{lim}} \]  

where \( f_z \) is the force exerted by the thrusters along \( z \), and \( w_{lim} \) is the linear speed of the ROV along \( z \). The estimated value of \( Z_w \) is 80 N.s.m^-1.

Now, to compute the parameter \( Y_v \), we have that the cross sectional area of the vehicle and also the shape of the body are quite the same in the \( z \) direction and in the \( y \) direction. Consequently, we consider that \( Y_v \) is roughly equal to \( Z_w \). The value of \( X_u \) is computed by measuring the time needed by the ROV to run a known horizontal distance in a pool, with a known horizontal thrust. Then, the speed is computed and the damping parameter is estimated. The estimated value of \( X_u \) is 30 N.s.m^-1. Regarding the rotational damping parameter, we applied a known torque along \( z \) axis with the thrusters and we recorded the rate of turn measured by the gyrometer (along \( z \) axis) of the embedded IMU. Once the rate of turn reaches its steady state value \( r_{lim} \), the rotational damping parameter \( N_r \) is approximated by:

\[ N_r \approx \gamma_z/r_{lim} \]  

where \( \gamma_z \) is the applied torque.

The estimated value of \( N_r \) is 2.9 N.m.s.rad^-1. The symmetry of the L2ROV vehicle allows us to consider that \( M_q \) is roughly equal to \( N_r \). The value of \( K_p \) (along \( x \) axis) is not be experimentally estimated as this would require to make the center of gravity coincide with the center of buoyancy. This is long and useless, since in our case the roll is naturally stable and is not controlled. According to the previous values and the geometry of the vehicle, we have considered that \( K_p = 1.4 \) N.m.s.rad^-1. Please note that we have assumed that the speed of the vehicle is sufficiently low to consider only the skin friction effects. Thus, we estimate only linear damping. Would the speed be higher, then quadratic damping would be taken into account and quadratic damping parameters should be computed by the same method, replacing each speed by its squared value. Given that the vehicle is moving slow and then, non diagonal terms of the damping matrix are neglected and only linear damping parameters have been estimated for this prototype, then

\[ D(\nu) = \text{diag}([30, 70, 80, 1.4, 2.5, 2.9]) \]  

in \( (\nu_z) \) (first three) and in \( (\nu_x, \nu_y) \) (last three).

2.2.2. Restoring forces and moments

The restoring forces and moments are generated by the weight \( f_W \) and the buoyancy force \( f_B \), this latter, always acts in the opposite direction of vehicle weight, that is:

\[ f_B = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \]  

\[ f_W = \begin{bmatrix} 0 \\ 0 \\ W \end{bmatrix} \]  

where \( B \) represents the magnitude of the buoyancy force, defined according to the Archimedes’ principle; \( W = mg \) is the vehicle’s weight, with \( g \) the gravitational acceleration. Notice that these forces are defined with respect to the earth-fixed-frame. Now, using the zyx-convention for navigation and control applications [5], the transformation matrix \( J(\eta) = R_y R_x R_z \) is introduced in order to obtain the buoyancy force and weight with respect to the body-fixed-frame:

\[ F_B = J(\eta_2)^{-1} f_B \]  

\[ F_W = J(\eta_2)^{-1} f_W \]  

Then, the restoring forces acting on the vehicle are \( F_B = F_B + F_W \), leading to:

\[ F_B = \begin{bmatrix} (B - W)\sin(\theta) \\ (B - W)\cos(\theta)\sin(\phi) \\ (B - W)\cos(\theta)\cos(\phi) \end{bmatrix} \]  

On the other hand, the restoring moments depend on the positions of the center of gravity (CG) and the center of buoyancy (CB), as we can notice in the following equation:

\[ m_x = r_w \times F_W + r_y \times F_B \]  

where \( r_w = [X_u, Y_v, Z_w]^T \) and \( r_y = [X_p, Y_p, Z_p]^T \) represent the positions of the center of gravity and the center of buoyancy, respectively. In our case the origin of the body-fixed-frame is chosen in the center of gravity, this implies that \( r_w = [0, 0, 0]^T \). While the center of buoyancy is \( r_y = [0, 0, -z_B]^T \). For practical purposes, the buoyancy force is greater than the weight, i.e. \( B - W = f_B > 0 \).
Then, from Eqs. (10) and (11), we obtain the vector of restoring forces and moments as follows:

$$
\mathbf{g}(\eta) = \begin{bmatrix} f_1 \\ m_g \end{bmatrix} = \begin{bmatrix} f_{s1}\sin(\theta) \\ -f_{s2}\cos(\theta)\sin(\phi) \\ -f_{s3}\cos(\theta)\cos(\phi) \\ -r_{\theta}R\cos(\theta)\sin(\phi) \\ -r_{\phi}B\sin(\theta) \\ 0 \end{bmatrix}
$$

(12)

2.2.3. Control inputs: forces and torques generated by the thrusters

The forces generated by the thrusters $f_1$ to $f_6$ and are denoted $f_1$ to $f_6$, and are defined by: $f_1 = [0.0, f_{11}]^T$, $f_2 = [0.0, f_{21}]^T$, $f_3 = [0.0, f_{31}]^T$, $f_4 = [f_{41}, 0.0]^T$, $f_5 = [f_{51}, 0.0]^T$, $f_6 = [0.0, f_{61}]^T$, as illustrated in Fig. 2. Then, the translation motions are produced by:

$$
\mathbf{\tau}_1 = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} f_4 + f_5 \\ f_6 \\ f_1 + f_2 + f_3 \end{bmatrix}
$$

(13)

and the torques generated by the above forces, are defined as follows:

$$
\mathbf{\tau}_2 = \sum_{i=1}^{6} \mathbf{l}_i \times \mathbf{f}_i
$$

(14)

where $\mathbf{l}_i = (l_{ix}, l_{iy}, l_{iz})$ is the position vector describing where the $f_i$ (for $i = 1, \ldots, 6$) forces apply, with respect to the body-fixed reference frame. The torques generated by the thrusters are then described by:

$$
\mathbf{\tau}_2 = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} l_{2x}f_2 + l_{3y}f_3 \\ l_{3x}f_2 + l_{3z}f_3 + l_{1x}f_1 \\ l_{4y}f_3 + l_{5y}f_5 \end{bmatrix}
$$

(15)

Finally, the vector of control inputs is expressed as follows:

$$
\mathbf{\tau} = \begin{bmatrix} f_4 + f_5 \\ f_6 \\ f_1 + f_2 + f_3 \\ l_{2x}f_2 + l_{3y}f_3 \\ l_{3x}f_2 + l_{3z}f_3 + l_{1x}f_1 \\ l_{4y}f_3 + l_{5y}f_5 \end{bmatrix}
$$

3. Proposed control strategy

In this section, nonlinear PD and PD+ controllers based on saturation functions with variable parameters are introduced. Both of them are proposed for set point regulation as well as for trajectory tracking control. The stability analysis of the resulting closed-loop system for both cases is detailed.

3.1. Nonlinear PD controller with gravity and buoyancy compensation

Considering the dynamics given by Eqs. (1) and (2), the PD control law with static feedback gains and gravity/buoyancy compensation is given by:

$$
\mathbf{\tau} = \mathbf{g}(\eta) - \mathbf{J}(\eta)\mathbf{\tau}_{PD}
$$

(17)

with

$$
\mathbf{\tau}_{PD} = \mathbf{K}_p\mathbf{e}(t) + \mathbf{K}_d\frac{\mathbf{de}(t)}{dt}
$$

(18)

where $\mathbf{K}_p, \mathbf{K}_d \in \mathbb{R}^{6 \times 6}$ are diagonal, positive definite matrices, and $\mathbf{e}(t) = \eta - \eta_d$ represents the error.

In order to improve the performance of the closed-loop system, we propose to introduce (in each term of Eq. (18)) a saturation function $\mathbf{\sigma}_g(h)$ illustrated in Fig. 4 and defined by:

$$
\mathbf{\sigma}_g(h) = \begin{cases} \bar{b} & \text{if } h > \bar{b} \\ b & \text{if } |h| \leq \bar{b} \\ -\bar{b} & \text{if } h < -\bar{b} \end{cases}
$$

(19)

where $\bar{b}$ is a positive constant, and $b$ represents a linear function. In our case, the terms to which this saturation will be applied are the error and its time derivative.

Then, if we introduce the above saturation function into in the control law (18), we obtain the following nonlinear PD (NLPD) controller:

$$
\mathbf{\tau}_{NLPD} = \mathbf{\sigma}_g[\mathbf{K}_p\mathbf{e}(t)] + \mathbf{\sigma}_g\left[\mathbf{K}_d\frac{\mathbf{de}(t)}{dt}\right]
$$

(20)

where

$$
\mathbf{\sigma}_g[\mathbf{K}_p\mathbf{e}(t)] = \begin{bmatrix} u_{g1} \\ 0 \\ \cdots \\ 0 \end{bmatrix} \begin{bmatrix} u_{g2} \\ 0 \\ \cdots \\ 0 \end{bmatrix}
$$

(21)

$$
\mathbf{\sigma}_g\left[\mathbf{K}_d\frac{\mathbf{de}(t)}{dt}\right] = \begin{bmatrix} u_{d1} \\ 0 \\ \cdots \\ 0 \end{bmatrix} \begin{bmatrix} u_{d2} \\ 0 \\ \cdots \\ 0 \end{bmatrix}
$$

(22)

with $u_{gj} = \sigma_{gj}[k_{gj}e_j(t)]$; $u_{dj} = \sigma_{dj}[k_{dj}\frac{de_j(t)}{dt}]$; where $k_{gj}, k_{dj}$ are positive constants, for all $j = 1, \ldots, n$.

Without loss of generality, let us consider now the scalar case, namely:

$$
\mathbf{\tau}_{NLPD1} = \sigma_{g1}[k_{p1}e_1(t)] + \sigma_{g1}\left[\mathbf{K}_d\frac{de_1(t)}{dt}\right]
$$

(23)

The above equation can be rewritten in a compact form as follows:

$$
\mathbf{\tau}_{NLPD1} = \sum_{i=1}^{2} u_i
$$

(24)

where $u_i = \sigma_{g1}(k_{hi})$ represents the saturation function, with $h_1 = \bar{b}_1$, $b_2 = \bar{b}_1$, $k_1 = k_{g1}$, $k_2 = k_{d1}$; $h_1$ is the error and $h_2$ its first derivative. Then, from Eq. (19) $u_i$ can be rewritten as:

$$
u_i = \begin{cases} \bar{b}_1 & \text{if } k_{hi} > \bar{b}_1 \\ h_1 & \text{if } |k_{hi}| \leq \bar{b}_1 \\ -\bar{b}_1 & \text{if } k_{hi} < -\bar{b}_1 \end{cases}
$$

(25)

In the above equation, we can notice that the linear function $k_{hi}$ is saturated by $|h_i| = \bar{b}_1/k_i$. At that time, we define:

$$
d_i := \bar{b}_1/k_i
$$

(26)

Then, we can rewrite Eq. (25) as follows:

$$
u_i = \begin{cases} \text{sign}(h_i)\bar{b}_1 & \text{if } |h_i| > d_i \\ h_id_i^{-1}\bar{b}_1 & \text{if } |h_i| \leq d_i \end{cases}
$$

(27)
where the tuning parameters of the controller are $b_i$ and $d_i$, $\forall i = 1, 2$. Moreover, considering that we have:

$$\text{sign}(h_i)\beta_i = h_i\text{sign}(h_i)\beta_i h_i^{-1}$$

which can be simplified as:

$$\text{sign}(h_i)\beta_i = |h_i|\beta_i h_i^{-1}$$

and considering that $|h_i| h_i^{-1} = |h_i|^{-1} h_i$, Eq. (27) can be rewritten as follows:

$$u_i = \begin{cases} \frac{b_i}{|h_i|} h_i^{-1} & \text{if} \quad |h_i| > d_i \\ \frac{b_i}{|d_i|} d_i^{-1} h_i & \text{if} \quad |h_i| \leq d_i \end{cases}$$

Consequently, the control law (23) can be rewritten as:

$$\tau_{\text{NLPD}} = u_1 + u_2 = k_{\text{p1}}(\cdot) e_1(t) + k_{\text{d1}}(\cdot) \dot{e}_1(t)$$

with:

$$k_{\text{p1}}(\cdot) = \begin{cases} \frac{b_{\text{p1}}(\cdot) e_1(t)^{-1}}{b_{\text{p1}}} & \text{if} \quad |e_1(t)| > d_{\text{p1}} \\ \frac{b_{\text{p1}}}{d_{\text{p1}}} d_{\text{p1}}^{-1} & \text{if} \quad |e_1(t)| \leq d_{\text{p1}} \end{cases}$$

$$k_{\text{d1}}(\cdot) = \begin{cases} \frac{b_{\text{d1}}(\cdot) e_1(t)^{-1}}{b_{\text{d1}}} & \text{if} \quad |\dot{e}_1(t)| > d_{\text{d1}} \\ \frac{b_{\text{d1}}}{d_{\text{d1}}} d_{\text{d1}}^{-1} & \text{if} \quad |\dot{e}_1(t)| \leq d_{\text{d1}} \end{cases}$$

The advantage of this formulation is that the forces and torques are limited by the parameters $b_{\text{p1}}$ and $b_{\text{d1}}$. Consequently, we are sure of the boundedness of the control input. However, some cases may require slightly larger forces and torques to correct the system errors, that is why we propose that the saturation value $\beta_i$ in Eq. (30) should be changed as follows:

$$\beta_i = b_i |h_i|^{-\mu_i} \quad \text{if} \quad |h_i| > d_i$$

and

$$\beta_i = b_i |d_i|^{-\mu_i} \quad \text{if} \quad |h_i| \leq d_i$$

with $\beta_i$ a positive constant, and $\mu_i \in [0, 1]$.

Now, introducing Eqs. (34) and (35) into (30), we obtain:

$$u_i = \begin{cases} \frac{b_i}{|h_i|^{1-\mu_i}} h_i^{-1} & \text{if} \quad |h_i| > d_i \\ \frac{b_i}{|d_i|^{1-\mu_i}} d_i^{-1} h_i & \text{if} \quad |h_i| \leq d_i \end{cases}$$

$\forall i = 1, 2$ and $\mu_i \in [0, 1]$.

The plots of the above function for different values of the parameter $\mu_i$ are shown in Fig. 5.

Consequently, the nonlinear PD control law based on saturation function with variable parameters can be expressed as:

$$\tau_{\text{NLPDj}} = k_{\text{pj}}(\cdot) e_j(t) + k_{\text{dj}}(\cdot) \dot{e}_j(t)$$

with:

$$k_{\text{pj}}(\cdot) = \begin{cases} \frac{b_{\text{pj}}(\cdot) e_j(t)^{1-\mu_{\text{pj}}} - 1}{b_{\text{pj}}} & \text{if} \quad |e_j(t)| > d_{\text{pj}} \\ \frac{b_{\text{pj}}}{d_{\text{pj}}} d_{\text{pj}}^{-1} & \text{if} \quad |e_j(t)| \leq d_{\text{pj}} \end{cases}$$

$$k_{\text{dj}}(\cdot) = \begin{cases} \frac{b_{\text{dj}}(\cdot) e_j(t)^{1-\mu_{\text{dj}}} - 1}{b_{\text{dj}}} & \text{if} \quad |\dot{e}_j(t)| > d_{\text{dj}} \\ \frac{b_{\text{dj}}}{d_{\text{dj}}} d_{\text{dj}}^{-1} & \text{if} \quad |\dot{e}_j(t)| \leq d_{\text{dj}} \end{cases}$$

where $\forall \mu_{\text{pj}}, \mu_{\text{dj}} \in [0, 1]$.

From Fig. 5, it can be noticed that if $\mu_{\text{pj}} = \mu_{\text{dj}} = 1$, the nonlinear PD controller given by (37) degenerates into the linear PD controller given by (18). Besides, if $\mu_{\text{pj}} = \mu_{\text{dj}} = 0$, we obtain the case of a constant saturation. To summarize, we can conclude that the linear PD controller and the nonlinear PD controller with a simple saturation function, defined by Eq. (19), are particular cases of the proposed controller.

**Theorem 1.** For the case of set-point regulation, under the nonlinear PD control (NLPD) with gravity compensation

$$\tau = g(\eta) - J^T(\eta)[K_p(\cdot) e + K_d(\cdot) \dot{e}]$$

where the feedback gains $K_p(\cdot)$ and $K_d(\cdot)$ have the following structure:

$$K_p(\cdot) = \begin{bmatrix} k_{p1}(\cdot) & 0 & \cdots & 0 \\ 0 & k_{p2}(\cdot) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{pm}(\cdot) \end{bmatrix} > 0$$

$$K_d(\cdot) = \begin{bmatrix} k_{d1}(\cdot) & 0 & \cdots & 0 \\ 0 & k_{d2}(\cdot) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{dn}(\cdot) \end{bmatrix} > 0$$

the system (1) is asymptotically stable if $k_{pj}(\cdot)$ and $k_{dj}(\cdot)$ are defined by (38) and (39) respectively and if the underwater vehicle is moving at low speed.

**Proof.** In the case of set-point regulation $\eta_d$ is constant, then $\dot{\eta}_d = 0$ and $\ddot{\eta} = \dot{\eta}$. As a consequence the control law given by Eq. (40) can be rewritten as:

$$\tau = g(\eta) - J^T(\eta)[K_p(\cdot) e + K_d(\cdot) \dot{\eta}]$$

In what follows we will suppose that $\theta \neq \pm \pi/2$, in order to avoid possible singularities of $J(\eta)$ matrix, see [5]. Now assuming that $\omega_e = 0$, the injection of the control law (43) into (1), leads to the following closed-loop system:

$$M\ddot{\mathbf{v}} + C(\mathbf{v})\dot{\mathbf{v}} + D(\mathbf{v})\mathbf{v} = -J^T(\eta)[K_p(\cdot) e + K_d(\cdot) \dot{\eta}]$$

and if we consider the transformation (2), we obtain:

$$M\ddot{\mathbf{v}} + C(\mathbf{v})\dot{\mathbf{v}} + D(\mathbf{v})\mathbf{v} = -J^T(\eta)[K_p(\cdot) e + K_d(\cdot) J(\eta)\mathbf{v}]$$

Let us define $K_{\text{dd}}(\cdot) = J^T(\eta)K_d(\cdot)J(\eta)$, then the previous equation can be rewritten as:

$$M\ddot{\mathbf{v}} + C(\mathbf{v})\dot{\mathbf{v}} + D(\mathbf{v})\mathbf{v} = -J^T(\eta)K_p(\cdot) e - K_{\text{dd}}(\cdot)\mathbf{v}$$

The closed-loop system (46) can be represented as

$$\frac{d}{dt} \begin{bmatrix} \mathbf{e} \\ \mathbf{v} \end{bmatrix} = \begin{bmatrix} \mathbf{e} \\ \mathbf{v} \end{bmatrix}$$

$$\begin{bmatrix} M^{-1}[-J^T(\eta)K_p(\cdot) e - K_{\text{dd}}(\cdot)\mathbf{v} - C(\mathbf{v})\dot{\mathbf{v}} - D(\mathbf{v})\mathbf{v}] \end{bmatrix}$$

Notice that the origin of the state space model is a unique equilibrium point. Now, in order to proof the asymptotic stability of the closed-loop system we propose the following Lyapunov function candidate:

$$V(\mathbf{e}, \mathbf{v}) = \frac{1}{2} \mathbf{v}^T M\mathbf{v} + \int_0^\infty \mathbf{e}^T K_p(\xi) d\xi$$

(47)
where
\[ f_0^t \xi^T K_p(\xi) d\xi = \left[ \int_0^t \xi_k^T k_{p1}(\xi_k) d\xi_k + \int_0^t \xi_{k2}^T k_{p2}(\xi_{k2}) d\xi_{k2} + \ldots + \int_0^t \xi_n^T k_{pn}(\xi_n) d\xi_n \right]. \]

Now, considering that the inequality
\[ e_j k_{pj}(\xi_j) \geq \alpha_j(|e_j|) \]
is satisfied with the class \( K \) functions
\[ \alpha_j(|e_j|) = \begin{cases} \frac{b_j}{a_j + |e_j|^a} & \text{if } |e_j| > d_j \\ \frac{b_j}{d_j^a} & \text{if } |e_j| \leq d_j \end{cases} \]
with \( b_{pj} > b_j, a > 0 \) and \( d_{pj} < d_j \). Then, according to Lemma 2 from [8] one deduces the following:
\[ \int_0^t \xi^T K_p(\xi) d\xi > 0 \quad \forall \ e \neq 0 \in \mathbb{R}^n \] (51)
and
\[ \int_0^t \xi^T K_p(\xi) d\xi \rightarrow \infty \quad \text{as } \| e \| \rightarrow \infty \] (52)

Therefore, the Lyapunov function candidate \( V(e, v) \) is positive definite and radially unbounded. Now, for underwater vehicles move at low speed the time differentiation of (48), along the trajectories of \( v \) and \( e \), is done with the assumption that \( M = M^T > 0 \). \( C(v) \) is skew symmetric and \( D(v) \) is definite positive, more details see [3]. Then, using the Leibniz’ rule for differentiation of integrals, the time derivative of the Lyapunov function candidate is:
\[ \dot{V}(e, v) = v^T M \dot{v} + e^T K_p(e) f(\eta) v \] (53)
by substituting the closed-loop Eq. (46) into (53) one obtains:
\[ \dot{V}(e, v) = -v^T J^T(\eta) K_p(e) e - v^T K_{d1}(\eta, e) \dot{v} \\
- v^T C(v) v - v^T D(v) v + e^T K_p(e) f(\eta) v \] (54)
since \( K_p(e) = K_p^T(e) \) and \( C(v) = -C^T(v) \), Eq. (54) becomes:
\[ \dot{V}(e, v) = -v^T \left[ K_{d1}(\eta, \dot{v}) + D(v) \right] v \] (55)

Recall that \( K_{d1} = K_{d1}^T > 0 \). therefore \( K_{d2} = K_{d2}^T > 0 \), and assuming that \( D(v) > 0 \), then one can conclude that \( \dot{V}(e, v) \) is negative semi-definite. Therefore the stability of the equilibrium point is guaranteed. In order to prove the asymptotic stability, the Krasovskii-LaSalle’s theorem can be used, let
\[ \Omega = \begin{bmatrix} e \\ v \end{bmatrix} : \dot{V}(e, v) = 0 \]
introducing \( v = 0 \) and \( \dot{v} = 0 \) into Eq. (46) leads to the unique invariant point \( e = 0 \). Therefore, we conclude that equilibrium point is asymptotically stable. \( \square \)

3.2. Nonlinear PD+ controller

For the case of trajectory tracking problem, we propose to use a nonlinear PD+ controller with the same feedback gains as the previous controller.

Based on Eq. (2), the following kinematic transformations can be obtained (see [5] for more details):
\[ \dot{\eta} = J(\eta) \dot{v} + f(\eta) v \quad \Rightarrow \quad \dot{\eta} = J^{-1}(\eta) \dot{\eta} - J^{-1}(\eta) J(\eta) \]

Applying the previous transformations to the dynamic model (1), one obtains:
\[ M_\eta(\eta) = J^{-1}(\eta) M J^{-1}(\eta) \]
\[ C_\eta(v, \eta) = J^{-1}(\eta) C(v) - M J^{-1}(\eta) \dot{J}(\eta) J^{-1}(\eta) \]
\[ D_\eta(v, \eta) = J^{-1}(\eta) D(v) J^{-1}(\eta) \]

where
\[ g_\eta(\eta) = J^{-1}(\eta) g(\eta) \]
\[ \tau_\eta(\eta) = J^{-1}(\eta) \tau \]

Consequently, the dynamic model (1) expressed in the earth-fixed-frame becomes:
\[ M_\eta(\eta) \ddot{\eta} + C_\eta(v, \eta) \dot{\eta} + D_\eta(v, \eta) \dot{\eta} + g_\eta(\eta) = J^{-1}(\eta) \tau \] (57)

**Theorem 2.** For the case of the trajectory tracking control, the nonlinear PD+ controller (NLDO+):
\[ \tau = -J^{-1}(\eta) [M_\eta(\eta) \ddot{\eta} + C_\eta(v, \eta) \dot{\eta} + D_\eta(v, \eta) \dot{\eta} + g_\eta(\eta) + K_p(\cdot)e + K_a(\cdot)\dot{e}] \] (58)

where the matrices \( K_p(\cdot) \) and \( K_{a}(\cdot) \) have the following structure:
\[ K_p(\cdot) = \begin{bmatrix} k_{p1}(\cdot) & 0 & \ldots & 0 \\
0 & k_{p2}(\cdot) & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & k_{pn}(\cdot) \end{bmatrix} > 0 \] (59)
\[ K_{a}(\cdot) = \begin{bmatrix} k_{a1}(\cdot) & 0 & \ldots & 0 \\
0 & k_{a2}(\cdot) & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & k_{an}(\cdot) \end{bmatrix} > 0 \] (60)

asymptotically stabilizes the system (1) if \( k_{pj}(\cdot) \) and \( k_{aj}(\cdot) \) are defined by (38) and (39) respectively and if the underwater vehicle is moving at low speed.

**Proof.** Injecting the control law (58) in Eq. (57), leads to the following closed-loop system:
\[ M_\eta(\eta) \ddot{\eta} + C_\eta(v, \eta) \dot{\eta} + D_\eta(v, \eta) \dot{\eta} - K_p(\cdot)e - K_{a}(\cdot)\dot{e} \] (61)
which can be rewritten as:
\[ \frac{\text{d}}{\text{d}t} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} \dot{e} \\ -M_\eta(\eta)^{-1} \left[ C_\eta(v, \eta) + D_\eta(v, \eta) + K_a(\cdot) \dot{e} + K_p(\cdot)e \right] \end{bmatrix} \] (62)

where it can be noticed that the resulting system is autonomous and the origin is its unique equilibrium point.

The stability analysis can be conducted in the same way as for the previous controller, then considering the following Lyapunov function candidate:
\[ V(e, \dot{e}) = \frac{1}{2} e^T M_\eta(\eta) \dot{e} + \int_0^t \xi^T K_p(\xi) d\xi \] (63)
and according to arguments used in proof of the previous section, we conclude that \( V(e, \dot{e}) \) is also positive definite and radially unbounded.

The time derivative of this Lyapunov function candidate gives:
\[ \dot{V}(e, \dot{e}) = e^T M_\eta(\eta) \dot{e} + \frac{1}{2} e^T M_\eta(\eta) \dot{e} + e^T K_p(\cdot)e \] (64)

Now, injecting Eq. (61) in (64), considering the assumption of Zero Wave Frequency and knowing that the vehicle is moving at slow speed we have that \( M_\eta = 0 \), \( C_\eta(v, \eta) \) is skew symmetric and \( D_\eta(v, \eta) > 0 \), more details see [3] and [5], then:
\[ \dot{V}(e, \dot{e}) = -e^T D_\eta(v, \eta) + K_a(\cdot) \dot{e} \] (65)
since \( K_a(\cdot) > 0 \) and symmetric matrix, we deduce that \( \dot{V}(e, \dot{e}) \) is negative semi-definite, and therefore we can conclude stability of
the equilibrium point. In order to prove asymptotic stability we apply the Krasovskii–LaSalle’s theorem. Consider the set $\Omega$ defined as:

$$\Omega = \left\{ \left[ \begin{array}{c} e \\ \dot{e} \end{array} \right] : \dot{V}(e, \dot{e}) = 0 \right\} = \left\{ \left[ \begin{array}{c} e \\ \dot{e} \end{array} \right] \in \mathbb{R}^2 \right\}$$

(66)

Introducing $\dot{e} = 0$ and $\ddot{e} = 0$ into Eq. (61), we deduce that the unique invariant set is defined by $e = 0$. As a consequence we conclude that equilibrium point is asymptotically stable. Notices that in case of $\eta_0$ constant, the nonlinear PD+ controller degenerates to the nonlinear PD controller presented in the previous section. Now, before to implementing the proposed control strategy it is important to know the behavior of the thrusters of the robot, consequently a series of experiments were conducted to obtain the relationship describing the force generated by thrusters in terms of the supply voltage, as illustrated in Fig. 6. In some works we can notice that the curve describing the behavior of the thrusters is approximately square, for instance in [16,15]. In our case the thrusters of the vehicle have a good behavior, which can help us in the experimental tests.

4. Real-time experimental results

Even though in this paper the stability analysis of the resulting closed-loop system with the proposed control strategy is addressed for the 6 degrees of freedom, the experimental results show only the behavior of two degrees of freedom, namely the yaw rotation and the depth translation along the z axis. Since in a lot of applications we need the vehicle to be close to $\theta = 0$ (pitch) and $\phi = 0$ (roll), which is possible thanks to the design of the vehicle, therefore we have decided to control only the yaw motion. In the case of translation motions we can control only the depth of the vehicle since it lacks a DVL or other sensor to estimate the positions X and Y.

The experimental setup consists of a small swimming pool with a capacity of 3000 l where the maximal depth is 1.2 m. From an experimental point of view, the main control goal is the validation of the nonlinear PD and nonlinear PD+ controllers with variable saturation for depth and yaw tracking, in the same time. The idea is also to show the effectiveness of the proposed control solution against possible changes in the buoyancy and damping parameters that may occur during the experiments. The experimental results proposed hereafter have been conducted through the implementation of the proposed controllers on the of L2ROV underwater vehicle, you can watch the real-time experiments in: www.youtube.com/watch?v=SZZm4He2-CA&feature=youtu.be.

4.1. Proposed experimental scenarios

From Theorem 3.2 we can notice that the nonlinear PD+ controller degenerate to a nonlinear PD controller when the desired trajectory is constant. Then, trajectory tracking control can be seen as an extension of set-point control. Moreover, from Theorem 3.1, it can be concluded that the nonlinear PD+ controller becomes a PD+ controller when $\mu_{pj} = \mu_{dj} = 1$. As a consequence, we consider implementing the nonlinear PD+ controller with the parameters’ values summarized in Table 2, and the desired depth and yaw trajectories depicted in Figs. 7 and 8, respectively.

Finally, in order to test the robustness of the proposed control schemes, the following scenarios are proposed for the previous cases:

- SCENARIO 1 : Nominal Case
  The main goal of this scenario is to tune the controller gains in order to get the best trajectory tracking performance. The gains are kept unchanged for the scenario 2.
- SCENARIO 2: Robustness towards uncertainties
  The objective of this scenario is to test the robustness of the proposed controllers when vehicle’s parameters (damping and buoyancy) are changed.

4.2. Scenario 1: nominal case

Given the characteristics of the control proposed in case 1, the gains of the control have been tuned in two steps. The first one is based on the Integral of Squared Time multiplied by Squared Error
(ISTSE) presented in [23]. In the second step the gains have been manually adjusted to get best results. The obtained parameters are summarized in Table 3.

The control parameters for the case 2 are given in Table 4, they are obtained by a heuristic method based on the following steps:

- First $d_{pj}$ is chosen, taking into account that the interval $[-d_{pj}, d_{pj}]$ is the linear region of the proposed controller.
- Considering $b_0 = 0$ and $\mu_{zj} = 0$; $b_{pj}$ is increased until the closed-loop system oscillates.
- $d_{pj}$ is chosen bigger than $d_{pj}$, and $\mu_{zj} = 0$.
- Then $b_{pj}$ is increased until the system oscillations decrease.
- Finally, $\mu_{pj}$ and $\mu_{zj}$ are adjusted to improve the system behavior, considering $\mu_{pj} < \mu_{zj}$.

Table 3

<table>
<thead>
<tr>
<th>Depth</th>
<th>$b_{zj} = 70$</th>
<th>$d_{zj} = \infty$</th>
<th>$\mu_{zj} = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>$b_{zj} = 5$</td>
<td>$d_{zj} = \infty$</td>
<td>$\mu_{zj} = 1$</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Depth</th>
<th>$b_{zj} = 20$</th>
<th>$d_{zj} = 0.05$</th>
<th>$\mu_{zj} = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>$b_{zj} = 4$</td>
<td>$d_{zj} = 5.72$</td>
<td>$\mu_{zj} = 0.09$</td>
</tr>
</tbody>
</table>

Two 200g buoyant floats, increasing the buoyancy of 330%

A 45cm x 10cm rigid plastic sheet, increasing the rotational damping along z axis of about 90%

The main goal of this scenario is to test the robustness of the proposed controllers towards uncertainties in the parameters of the model. During the real-time experiments, we have added two 200 g buoyant floats (as illustrated in Fig. 9), increasing the buoyancy of 330%, and a large (45 cm x 10 cm) rigid plastic sheet (as illustrated in Fig. 9), increasing the rotational damping along z axis of about 90%.

Fig. 10–(a) shows the obtained results for trajectory tracking in depth, the corresponding tracking error, and the control input for the controller defined in Case 1. Fig. 10–(b) shows the evolution of the tracking in yaw, the corresponding tracking error, and the control input produced by the thrusters.

Fig. 11–(a) depicts the experimental results for trajectory tracking in depth, the corresponding tracking error, and the control input for the controller defined in Case 2. Fig. 11–(b) shows the evolution of the tracking in yaw, the corresponding tracking error and the yaw control input. Moreover, we can observe that the yaw motion converges to the desired trajectory in less than 1.5 s.

In order to evaluate the tracking performance of the proposed controllers, let us compute the Root Mean Square Error (RMSE) for $z$ and $\psi$. In addition, the integral of control inputs (the applied force and torque) are computed to estimated the energy consump-

tion used in each case, that is:

$$ INT = \int_{t_1}^{t_2} | \tau(t) | \, dt $$

(67)

where $t_1 = 2$ s, since in this time for both cases the system's states are close to their desired values, and $t_2 = 30$ s.

From the results of Table 5, we observe that the RMSE$_{z}$ and RMSE$_{\psi}$ of case 2 are smaller than in case 1. It can be observed that steady-state errors $z$ and $\psi$ are approximately 8.7 mm and 0.04 deg for the case 1, while for the case 2 are approximately 4.4 mm and 0.03 deg respectively. Moreover, notice that the quotients between INT$_{z}$ and INT$_{\psi}$ from case 1 and 2 are:

$$ \frac{491.62}{721.36} = 0.6953 $$

(68)

This means that energy consumption for trajectory tracking in depth, using the controller defined in Case 2, is 0.695 times the energy consumption using the controller defined in Case 1. While energy consumption for trajectory tracking in heading, using the controller defined in Case 2, is 1.27 times the energy consumption using the controller defined in Case 1.

4.3. Scenario 2: robustness test

The obtained experimental results for case 1 are shown in Fig. 12. The tracking performance of the control system for depth is degraded. Indeed, depth control of the vehicle was not able to reach the desired trajectory. We can notice that steady-state error on $z$ and $\psi$ are approximately 11 cm and 0.01 deg, respectively. For the yaw motion, the vehicle converges to the desired trajectory in less than 1 s (as noticed in Fig. 12–(a)). The force $\tau_{z}$ and torque $\tau_{\psi}$ generated by the thrusters are displayed at the bottom curves of Fig. 12.

Fig. 13 shows that the performance of the system is less affected in case 2. Indeed, it can be observed that the steady-state errors on $z$ and $\psi$ are approximately 6 cm and 0.006 deg, respectively. The yaw motion is the less affected, since the vehicle converges to the desired trajectory in less than 1 s. The generated control input (force $\tau_{z}$ and torque $\tau_{\psi}$) are displayed in the bottom curves of Fig. 13.

Now, the RMSE and the integral of the applied force and torque for both cases are summarized in Table 6:

According to Table 6 the quotients between INT$_{z}$ and INT$_{\psi}$ from case 1 and 2 are:

$$ \frac{19831}{19356} = 1.0245 $$

(69)

$$ \frac{721.36}{611.19} = 1.1803 $$

(70)
Fig. 10. Experimental results of scenario 1 in the case 1: trajectory tracking of depth and yaw versus time, error signal of both motions and evolution of the control inputs generated by the thrusters.

Fig. 11. Experimental results of scenario 1 in the case 2: trajectory tracking of depth and yaw versus time, error signal of both motions and evolution of the control inputs generated by the thrusters.
This means that energy consumption for trajectory tracking in depth, using the controller defined in Case 2, is 1.05 times the energy consumption using the controller defined in Case 1. While energy consumption for trajectory tracking in heading, using the controller defined in Case 2, is 1.27 times the energy consumption using the controller defined in Case 1. We can observe that the quotients obtained in this scenario are very similar as in the previous scenario, see Eq. (68). Moreover, one can notice that the closed-loop system with the nonlinear PD+ controller, represented by case 2, is less affected. It can be observed that steady-state er-
rors $z$ and $\psi$ are approximately 11 cm and 0.01 deg for the case 1, while for the case 2 their values are approximately 6 cm and 0.006 deg respectively. Moreover, notice that the chattering is large in the second case than in the first one. This is due to the stronger compromise between performance and robustness imposed by the variable saturation case. Then, we can conclude that the proposed control strategy demonstrated a good ability to deal with parameters’ uncertainties.

5. Conclusion and future work

In this paper, a nonlinear PD and PD+ controllers have been proposed for depth and yaw control of underwater vehicles. The stability analysis for the resulting closed-loop system for both set-point regulation and trajectory tracking control has been addressed. The proposed controllers have been implemented for trajectory tracking in depth and yaw motions with the L2ROV underwater vehicle. The obtained experimental results demonstrate the effectiveness and the robustness of the proposed controllers towards uncertainties on the parameters of the system (damping and buoyancy changes). The future work will consist in implementing the integral term of the controller in order to improve the steady-state performance of the closed-loop system.

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