A NEURAL NETWORK BASED CONTROLLER FOR UNDERWATER ROBOTIC VEHICLES

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Abstract. *Due to the enormous technological improvements obtained in the last decades it is possible to use robotic vehicles for underwater exploration. This work describes the development of a dynamic positioning system for remotely operated underwater vehicles based. The adopted approach is developed using Lyapunov Stability Theory and enhanced by a neural network based algorithm for uncertainty and disturbance compensation. The performance of the proposed control scheme is evaluated by means of numerical simulations.*

Keywords: *Adaptive algorithms, Dynamic positioning, Neural Networks, Nonlinear Control, Remotely Operated underwater Vehicles.*

1. INTRODUCTION

The control system is one of the most important peaces of a Remotely Operated underwater Vehicle (ROV), and its characteristics (advantages and disadvantages) play an essential role when one have to choose a vehicle for a specific mission. These vehicles have been substituting the divers in the accomplishment of tasks that offer risks to the human life. In this way, ROVs have been used thoroughly in the research of sub phenomena and in assembly, inspection, and repair of offshore structures. During the execution of a certain task with the robotic vehicle, the operator needs to monitor and control a series of parameters. If some of these parameters, as for instance the position and attitude of the vehicle, could be attended automatically by a control system, the teleoperation of the ROV can be enormously facilitated.

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.

Due to the adaptive capabilities of the artificial neural networks, it 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 has been made to combine artificial neural networks with nonlinear control methodology.

In this work, a nonlinear controller scheme with a neural network based compensation scheme is employed for the dynamic positioning of underwater vehicles. Based on a Lyapunov stability theory , the convergence properties of the closed-loop system is analytically proven. Numerical results are also provided to confirm the control system efficacy.

2. NONLINEAR CONTROLLER DESIGN

Consider a class of nth-order nonlinear systems:

$$x^{(n)} = f(\mathbf{x}) + b(\mathbf{x})u + d \tag{1}$$

where u is the control input, the scalar variable x is the output of interest, $x^{(n)}$ is the n-th time derivative of x, $\mathbf{x} = [x, \dot{x}, \ldots, x^{(n-1)}]$ is the system state vector, d represents external disturbances and unmodeled dynamics, and $f, b : \mathbb{R}^n \to \mathbb{R}$ are both nonlinear functions.

As demonstrated by Bessa and Barrêto (2010), adaptive fuzzy algorithms can be properly combined with nonlinear controllers in order to improve the trajectory tracking of uncertain nonlinear systems. It has also been shown that such strategies are suitable for a variety of applications ranging from remotely operated underwater vehicles (Bessa *et al.*, 2008, 2010) to chaos control (Bessa *et al.*, 2009).

The proposed control problem is to ensure that the state vector $\mathbf{x}$ will follow a desired trajectory $\mathbf{x}_d = [x_d, \dot{x}_d, \ldots, x_d^{(n-1)}]$ in the state space. Regarding the development of the control law, the following assumptions should also be made:

Assumption 1 *The state vector $\mathbf{x}$ is available.*

Assumption 2 *The desired trajectory $\mathbf{x}_d$ is once differentiable in time. Furthermore, every element of vector $\mathbf{x}_d$, as well as $x_d^{(n)}$, is available and with known bounds.*

Let $\tilde{x} = x - x_d$ be defined as the tracking error in the variable x, and

$$\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_d = [\tilde{x}, \dot{\tilde{x}}, \ldots, \tilde{x}^{(n-1)}]$$

as the tracking error vector. Now, consider a combined tracking error measure:

$$\varepsilon = \mathbf{c}^{\mathrm{T}}\tilde{\mathbf{x}} \tag{2}$$

where $\mathbf{c} = [c_{n-1}\lambda^{n-1}, \ldots, c_1\lambda, c_0]$, λ is positive constant and c_i states for binomial coefficients, i.e.,

$$c_i = \binom{n-1}{i} = \frac{(n-1)!}{(n-i-1)!\,i!}, \qquad i = 0, 1, \ldots, n-1 \tag{3}$$

which makes $c_{n-1}\lambda^{n-1} + \cdots + c_1\lambda + c_0$ a Hurwitz polynomial.

From Eq. (3), it can be easily verified that $c_0 = 1$, for $\forall n \geq 1$. Thus, for notational convenience, the time derivative of ε will be written in the following form:

$$\dot{\varepsilon} = \mathbf{c}^{\mathrm{T}}\dot{\tilde{\mathbf{x}}} = \tilde{x}^{(n)} + \bar{\mathbf{c}}^{\mathrm{T}}\tilde{\mathbf{x}} \tag{4}$$

where $\bar{\mathbf{c}} = [0, c_{n-1}\lambda^{n-1}, \ldots, c_1\lambda]$.

Based on Assumptions 1 and 2, the following control law can be proposed:

$$u = \frac{1}{b}\left(-f - d + x_d^{(n)} - \bar{\mathbf{c}}^{\mathrm{T}}\tilde{\mathbf{x}} - \kappa\varepsilon\right) \tag{5}$$

where κ is a strictly positive constant.

The boundedness and convergence properties of the closed-loop system are established in the following theorem.

Theorem 1 *Consider the nonlinear system (1) and Assumptions 1–2. Then, the controller defined by (5) ensures the exponential convergence of the tracking error, i.e., $\tilde{\mathbf{x}} \to \mathbf{0}$ as $t \to \infty$.*

Proof: Let a positive definite Lyapunov function candidate V be defined as

$$V(t) = \frac{1}{2}\varepsilon^2 \tag{6}$$

Thus, the time derivative of V is

$$\dot{V}(t) = \varepsilon\dot{\varepsilon} = (\tilde{x}^{(n)} + \bar{\mathbf{c}}^{\mathrm{T}}\tilde{\mathbf{x}})\varepsilon = (x^{(n)} - x_d^{(n)} + \bar{\mathbf{c}}^{\mathrm{T}}\tilde{\mathbf{x}})\varepsilon = \left[f + b\,u + d - x_d^{(n)} + \bar{\mathbf{c}}^{\mathrm{T}}\tilde{\mathbf{x}}\right]\varepsilon$$

By applying the proposed control law (5), one has

$$\dot{V}(t) = -\kappa\varepsilon^2 \tag{7}$$

which implies $\varepsilon \to 0$ as $t \to \infty$.

From the definition of limit, it means that for every $\xi > 0$ there is a corresponding number τ such that $|\varepsilon| < \xi$ whenever $t > \tau$. According to Eq. (2) and considering that $|\varepsilon| < \xi$ may be rewritten as $-\xi < \varepsilon < \xi$, one has

$$-\xi < c_0 \tilde{x}^{(n-1)} + c_1 \lambda \tilde{x}^{(n-2)} + \cdots + c_{n-2} \lambda^{n-2} \dot{\tilde{x}} + c_{n-1} \lambda^{n-1} \tilde{x} < \xi \tag{8}$$

Multiplying (8) by $e^{\lambda t}$ and noting that

$$\frac{d^{n-1}}{dt^{n-1}}(\tilde{x} e^{\lambda t}) = \left(c_0 \tilde{x}^{(n-1)} + c_1 \lambda \tilde{x}^{(n-2)} + \cdots + c_{n-2} \lambda^{n-2} \dot{\tilde{x}} + c_{n-1} \lambda^{n-1} \tilde{x} \right) e^{\lambda t}$$

one has

$$-\xi e^{\lambda t} < \frac{d^{n-1}}{dt^{n-1}}(\tilde{x} e^{\lambda t}) < \xi e^{\lambda t} \tag{9}$$

Thus, integrating (9) $n - 1$ times between 0 and t gives

$$-\frac{\xi}{\lambda^{n-1}} e^{\lambda t} + \left(\left| \frac{d^{n-2}}{dt^{n-2}}(\tilde{x} e^{\lambda t}) \right|_{t=0} + \frac{\xi}{\lambda} \right) \frac{t^{n-2}}{(n-2)!} + \cdots + \left(|\tilde{x}(0)| + \frac{\xi}{\lambda^{n-1}} \right) \leq \tilde{x} e^{\lambda t} \leq \frac{\xi}{\lambda^{n-1}} e^{\lambda t} +$$
$$+ \left(\left| \frac{d^{n-2}}{dt^{n-2}}(\tilde{x} e^{\lambda t}) \right|_{t=0} - \frac{\xi}{\lambda} \right) \frac{t^{n-2}}{(n-2)!} + \cdots + \left(|\tilde{x}(0)| - \frac{\xi}{\lambda^{n-1}} \right) \tag{10}$$

Furthermore, dividing (10) by $e^{\lambda t}$, it can be easily verified that the values of $\tilde{x}$ can be made arbitrarily close to 0 (within a distance ξ) by taking t sufficiently large (larger than τ), i.e., $\tilde{x} \to 0$ as $t \to \infty$. Now, considering the $(n-2)^{\text{th}}$ integral of (9), dividing again by $e^{\lambda t}$ and considering that $\tilde{x}$ converges to zero, it follows that $\dot{\tilde{x}} \to 0$ as $t \to \infty$. The same procedure can be successively repeated until the convergence of each component of the tracking error vector is achieved: $\tilde{\mathbf{x}} \to \mathbf{0}$ as $t \to \infty$. $\qquad\square$

3. VEHICLE DYNAMICS MODEL

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.*, 2010, 2008; Antonelli, 2007; Hoang and Kreuzer, 2007; Smallwood and Whitcomb, 2004; Hsu *et al.*, 2000; 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:

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{k}(\boldsymbol{\nu}) + \mathbf{h}(\boldsymbol{\nu}) + \mathbf{g}(\mathbf{x}) + \mathbf{d} = \boldsymbol{\tau} \tag{11}$$

where $\boldsymbol{\nu} = [v_x, v_y, v_z, \omega_x, \omega_y, \omega_z]$ 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.

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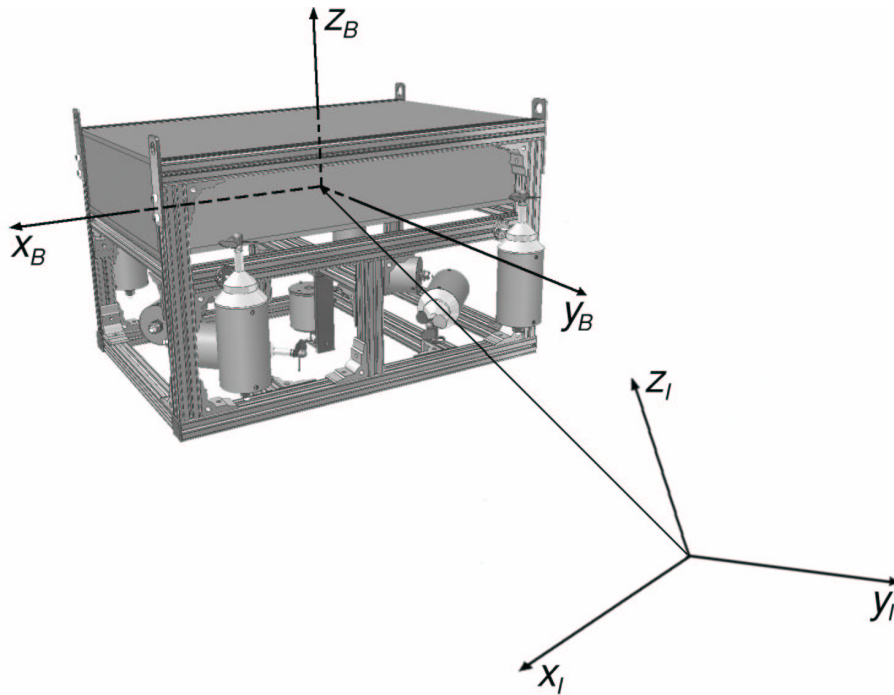
Figure 1. Underwater vehicle with both inertial and body-fixed reference frames.

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.*, 2000; 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 **d**.

On this basis, considering that the restoring forces can be passively compensated (Kiriazov *et al.*, 1997), the most relevant hydrodynamic forces and moments acting on ROVs are discussed in the following subsections.

3.1 Hydrodynamic forces

Remotely operated underwater vehicles typically operate with velocities never exceeding 2 m/s. Consequently, the hydrodynamic forces (F_h) can be approximated using the *Morison equation* (Newman, 1986):

$$F_h = \frac{1}{2}C_D A \rho\, v|v| + C_M \rho \nabla \dot{v} + \rho \nabla \dot{v}_w \tag{12}$$

where v and $\dot{v}$ are, respectively, the relative velocity and the relative acceleration between rigid-body and fluid, $\dot{v}_w$ is the acceleration of underwater currents, A is a reference area, ρ is the fluid density, ∇ is the fluid's displaced volume, C_D and C_M are coefficients that must be obtained experimentally.

The last term of Eq. (12) is the so-called *Froude-Kryloff force* and will not be considered in this work due the fact, that at normal working depths, the acceleration of the underwater currents is negligible. In this way, the coefficient $C_M \rho \nabla$ of the second term will be called hydrodynamic added mass. The first term represents the nonlinear hydrodynamic quadratic damping. Experimental tests (Kleczka *et al.*, 1992) show that Morison equation describes with sufficient accuracy the hydrodynamic effects due to the relative motion between rigid-bodies and water.

3.1.1 Quadratic Damping

The effects of the hydrodynamic damping $\mathbf{h}(\boldsymbol{\nu})$ over the vehicle, due not only to the translational but also to rotational motions, can be described in the body-fixed reference frame by:

$$\mathbf{h}(\boldsymbol{\nu}) = \frac{1}{2}\rho\left[C_{D_x}v_x|v_x|, C_{D_y}v_y|v_y|, C_{D_z}v_z|v_z|, C_{D_\gamma}\omega_z|\omega_z|\right] \tag{13}$$

where the parameters C_{D_x}, C_{D_y}, C_{D_z} and C_{D_γ} depend on the geometry of the vehicle and should be obtained experimentally in a wind tunnel (Pinto, 1996), or on-line estimated with adaptive algorithms in a water tank (Smallwood and Whitcomb, 2003).

3.1.2 Added inertia

Considering that an underwater vehicle typically operates at low speeds, the added inertia matrix, $\mathbf{M}_A \in \mathbb{R}^{4\times4}$, could be assumed as diagonally dominant and described as follows:

$$\mathbf{M}_A = \mathrm{diag}\left\{C_{M_x}\rho\nabla\,,\,C_{M_y}\rho\nabla\,,\,C_{M_z}\rho\nabla\,,\,C_{M_\gamma}\rho\nabla\right\} \tag{14}$$

As with the computation of the hydrodynamic damping, the coefficients C_{M_x}, C_{M_y}, C_{M_z} and C_{M_γ} should be determined experimentally. The matrix $\mathbf{M}_A$ must be combined with the rigid-body inertia matrix in order to obtain the matrix $\mathbf{M}$ of Eq. (11).

4. DYNAMIC POSITIONING SYSTEM

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

Considering that the control law for each degree of freedom can be easily designed with respect to the inertial reference frame, Eq. (11) should be rewritten in this coordinate system.

Remembering that

$$\dot{\mathbf{x}} = \mathbf{J}(\mathbf{x})\boldsymbol{\nu} \tag{15}$$

where $\mathbf{J}(\mathbf{x})$ is the Jacobian transformation matrix, it can be directly implied that

$$\boldsymbol{\nu} = \mathbf{J}^{-1}(\mathbf{x})\dot{\mathbf{x}} \tag{16}$$

and

$$\dot{\boldsymbol{\nu}} = \dot{\mathbf{J}}^{-1}\dot{\mathbf{x}} + \mathbf{J}^{-1}\ddot{\mathbf{x}} \tag{17}$$

Therefore, the equations of motion of an underwater vehicle, with respect to the inertial reference frame, becomes

$$\bar{\mathbf{M}}\ddot{\mathbf{x}} + \bar{\mathbf{k}} + \bar{\mathbf{h}} + \bar{\mathbf{d}} = \bar{\boldsymbol{\tau}} \tag{18}$$

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

In order to develop the control law with a decentralized approach, Eq. (18) can be rewritten as follows:

$$\ddot{x}_i = \bar{m}_i^{-1}(\bar{\tau}_i - \bar{k}_i - \bar{h}_i - \bar{d}_i); \quad i = 1, 2, 3, 4, \tag{19}$$

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 $\mathbf{J}^{-T}\mathbf{M}\mathbf{J}^{-1}$. The off-diagonal terms of $\mathbf{J}^{-T}\mathbf{M}\mathbf{J}^{-1}$ are incorporated in the vector $\bar{\mathbf{d}}$.

For notational simplicity the index i will be suppressed in Eq. (19) and, in this way, the equation of motion for each degree of freedom (DOF) becomes:

$$\ddot{x} = \bar{m}^{-1}(\bar{\tau} - \bar{k} - \bar{h} - \bar{d}) \tag{20}$$

On this basis, according to Eq. (5) and considering $\varepsilon = \dot{\tilde{x}} + \lambda_i \tilde{x}$, the following could be proposed for each DOF:

$$\bar{\tau} = \bar{k} + \bar{h} + \bar{d} + \bar{m}\left(\ddot{x}_d - \lambda \dot{\tilde{x}}\right) - \kappa\varepsilon \tag{21}$$

But since disturbances are unknown, in this work the value of d will be estimated using a three-layer artificial neural network.

$$\hat{d} = \mathbf{W}^{\mathrm{T}}\sigma(\mathbf{V}^{\mathrm{T}}\boldsymbol{\theta}) \tag{22}$$

where $\mathbf{W}$ and $\mathbf{V}$ are the weight matrices in, respectively, hidden and output layers. The vector $\boldsymbol{\theta}$ represents the network input. Standard sigmoid functions are used in hidden layer and the output layer has a linear activation function. The weights could be online updated using the conventional backpropagation scheme.

In this way, the resulting control law could be written as follows:

$$\bar{\tau} = \bar{k} + \bar{h} + \hat{\bar{d}} + \bar{m}\left(\ddot{x}_d - \lambda\dot{\tilde{x}}\right) - \kappa\varepsilon \tag{23}$$

5. SIMULATION RESULTS

In order to evaluate the control system performance, three different numerical simulations were performed for the depth regulation of an underwater robotic vehicle. The obtained results were presented from Fig. 2 to Fig. 5.

In the first case, it was considered that the initial state coincides with the initial desired state, $\tilde{\mathbf{z}}(0) = [\tilde{z}(0), \dot{\tilde{z}}(0)]^{\mathrm{T}} = \mathbf{0}$. Figure 2 gives the corresponding results for the tracking of $z_d = 0.5[1 - \cos(0.1\pi t)]$. Regarding controller and model parameters, the following values were chosen $\bar{m} = 50$ kg, $\bar{h} = 250$ Ns^2/m^2, $\kappa = 3.5$ and $\lambda = 3.5$. The capability of the proposed scheme to deal with uncertainties was appraised by choosing the parameters for the controller based on the assumption that exact values are not known but with a maximal uncertainty of $\pm 10\%$ over adopted values for the model parameters.
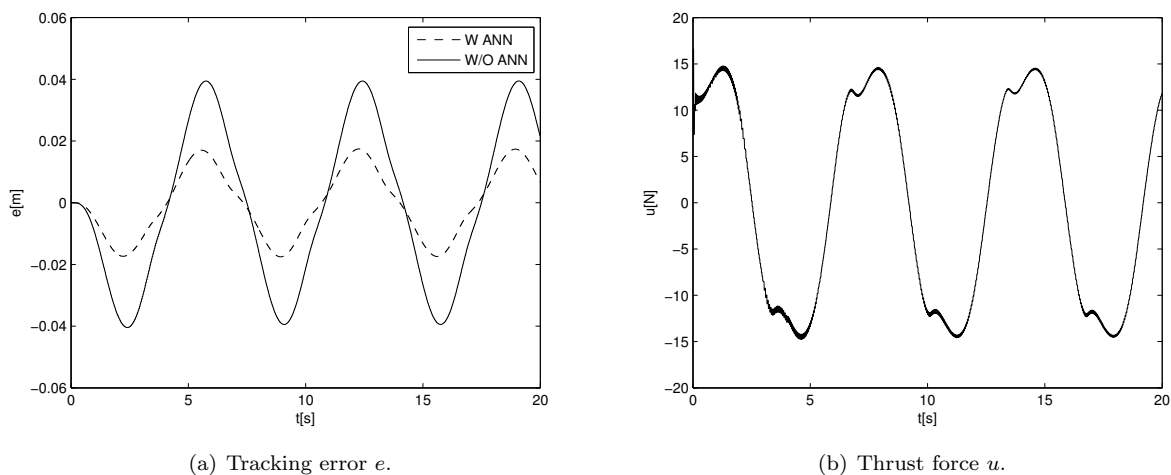

(a) Tracking error e.

(b) Thrust force u.

Figure 2. Tracking with $z_d = 0.5[1 - \cos(0.1\pi t)]$ and $\tilde{\mathbf{z}}(0) = \mathbf{0}$.

As observed in Fig. 2, the proposed control scheme allows the underwater robotic vehicle to track the desired trajectory with a small tracking error. Through the comparative analysis showed in Fig. 2(a), the improved performance of the proposed controller over the uncompensated counterpart can be easily ascertained.

In the second simulation the initial state and initial desired state are not equal, $\tilde{\mathbf{z}}(0) = [0.1, 0.0]$. The controller and model parameters and the desired trajectory were defined as before. Figures 3 and 4 show the corresponding results, respectively, with and without the neural network compensation scheme.
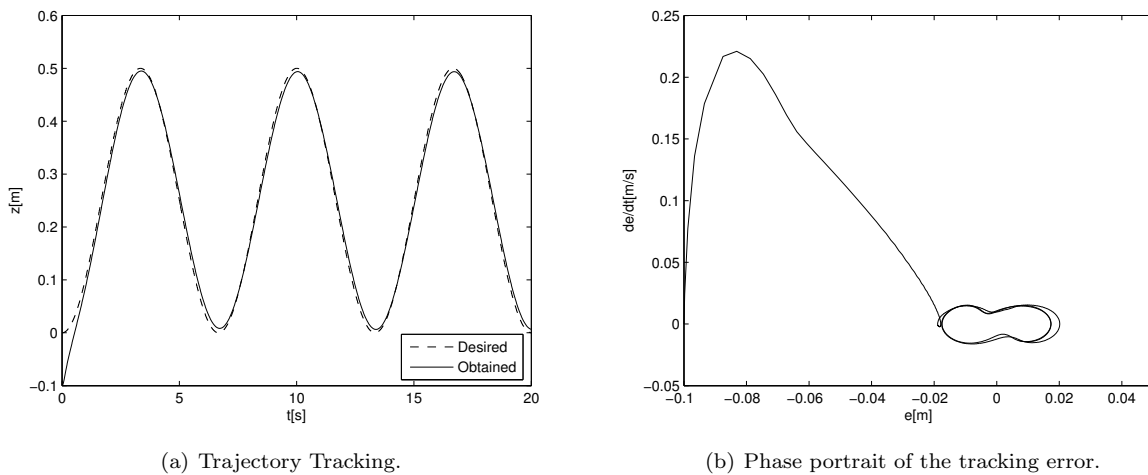
(a) Trajectory Tracking.

(b) Phase portrait of the tracking error.

Figure 3. Tracking with $\tilde{\mathbf{z}}(0) = [0.1, 0.0]$ and ANN compensation.

(a) Trajectory Tracking.

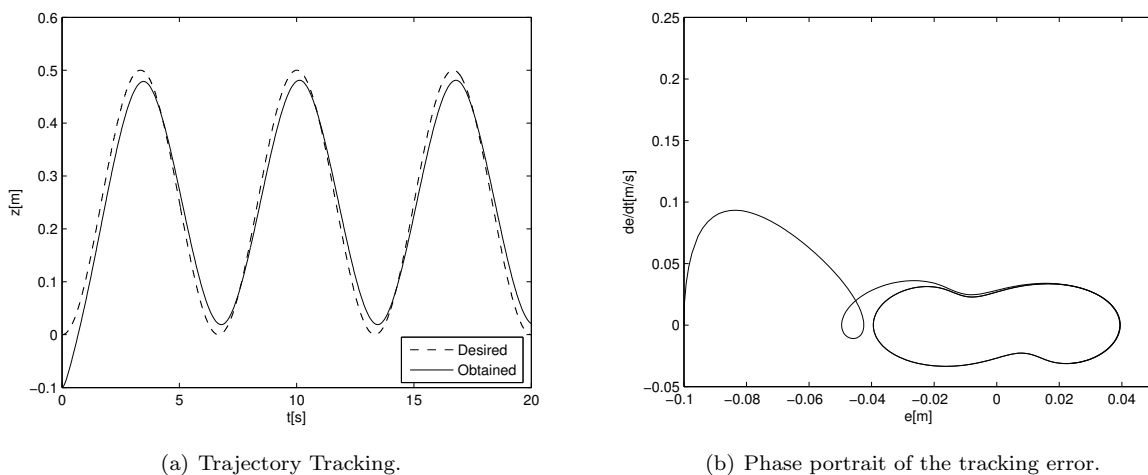(b) Phase portrait of the tracking error.

Figure 4. Tracking with $\tilde{\mathbf{z}}(0) = [0.1, 0.0]$ but without ANN compensation.

As observed in Fig. 3(a), even if the initial state and initial desired state are not equal, the proposed control scheme allows the trajectory tracking with a small tracking error. By comparing Fig. 3(b) and Fig. 4(b), it can be verified that the adoption of a neural-network compensation scheme leads to a smaller limit cycle in the phase portrait related to the tracking error. Although the compensation scheme improves the tracking performance, a larger overshoot with respect to velocity error can be seen in Fig. 3(b). This overshoot is due to the fact that the initial tracking error is different of zero. In order to avoid this phenomenon, we will let the neural-network compensator to wait for 2 seconds until it starts. Figure 5 shows the obtained results.

6. CONCLUDING REMARKS

In this paper, a nonlinear controller was proposed to deal with the dynamic positioning system for underwater robotic vehicles. To enhance the tracking performance the adopted strategy embedded an artificial neural-network based scheme within the conventional nonlinear controller for uncertainty/disturbance compensation. The stability and convergence properties of the closed-loop systems were analytically proven using Lyapunov stability theory. Through numerical simulations, the improved performance over the uncompensated control strategy was demonstrated.

7. ACKNOWLEDGEMENTS

(a) Trajectory Tracking.

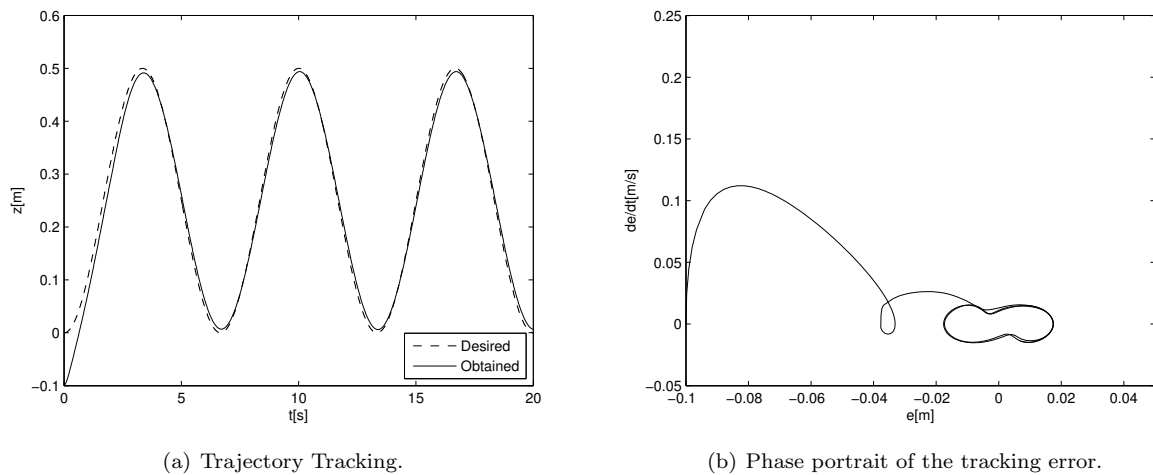(b) Phase portrait of the tracking error.

Figure 5. Tracking with $\tilde{\mathbf{z}}(0) = [0.1, 0.0]$ and ANN compensation starting after 2 s.

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