中國機械工程學刊第三十九卷第三期第 319~328 頁(民國一百零七年)
Journal of the Chinese Society of Mechanical Engineers, Vol.39, No.3, pp 319~328 (2018)

Nonlinear Guidance Law Design of Autonomous Underwater Vehicles

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Keywords： Autonomous underwater vehicle (AUV), nonlinear guidance law, waypoint-tracking design, 3D space, six degrees of freedom (6 DOF).

ABSTRACT

One novel nonlinear guidance law for guiding autonomous underwater vehicles (AUVs) to track desired waypoints in three-dimensional (3D) space with a nonlinear proportional derivative (PD) control structure is developed in this investigation. This approach can be applied to generate optimal control commands for AUVs operating in ocean environment. The design objective of this investigation is to develop a nonlinear guidance law, which guarantees the stability and convergence of tracking errors in positions and attitudes with respect to the highly coupled AUV's dynamics and kinematics. In general, it is really a difficult mission to treat this nonlinear waypoint-tracking problem of AUVs due to the high nonlinearity and the time-varying property of the controlled AUV's dynamics. Fortunately, because of the coordinate transformation and selection of the control gain, the mentioned nonlinear waypoint-tracking problem of AUVs can be effectively solved, and a promising waypoint tracking capability can be obtained for AUVs.

INTRODUCTION

AUVs were developed in the past two decades for executing missions, such as mine reconnaissance, marine environmental survey, and oil and gas exploitation, etc (Antonelli ; Bernstein; Bloch; Bryson) [1–4]. For meeting these specific goals, how to guide an AUV along a predefined trajectory in vast and hostile marine environments precisely becomes the major and challenging task of the waypoint-tracking design of AUVs. The success rate of the waypoint-tracking design of AUVs is highly reduced due to several inevitable reasons: 1. Unpredictable environmental disturbances induced by ocean currents, 2. Nonlinear coupled dynamics, 3. Noisy underwater acoustic communication, and so on [5–8].

Paper Received Juane, 2017. Revised August, 2017. Accepted December, 2018. Author for Correspondence: Yung-Yue Chen.

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Besides, the guided AUV must move to a specific point in 3D space at a pre-defined time instant in the trajectory-tracking task; hence, the space and time requirements are mixed into the tracking problem of AUVs [9–12]. General speaking, the waypoint-tracking design of AUVs is different with the trajectory following design because of the extra time assignment. For solving the waypoint-tracking problem, various efforts developed for two-dimensional (2D) AUVs are investigated such as backstepping control design [13], intelligent control design [14-15], and sliding mode control design [16]. Although, the above achievements provide acceptable tracking performances for AUVs in 2D space. However, these reduced order control designs did not meet the practical situation of a guided AUV in three-dimensional (3D) space. 3D waypoint-tracking design of AUVs is a more complicated task with respect to the motivated 2D waypoint-tracking design due to the strongly coupled dynamics. To the best knowledge of the authors, investigations of guidance law designs concerning the 3D waypoint-tracking requirement for AUVs are a few, and most of them are based on the kinematics of AUVs without taking the dynamics into consideration. Recently, a hybrid control design for tracking a 3D *S*-shaped trajectory is studied based on *D*-implementation method in [17]. Another applied the well-known gain scheduling control methodology to the infant AUV is proposed in [18]. In [19-20], a complex backstepping technique based on the tracking error dynamics between the guided AUV and the related trajectory was built up. A feedback tracking control scheme with a full-state feedback design based on the Lyapunov analysis was developed to drive the AUV to move along a *U*-shaped trajectory [21]. From the simulation results, the chattering phenomena in position errors is revealed as in [21]. An adaptive backstepping control design which guaranteed the trajectory-tracking performance was developed to treat the model uncertainties [24]. However, the control structure of this proposed method is too complex, and a high calculation power is always needed.

According to the above considerations in the control or guidance designs of AUVs, a nonlinear PD type guidance law is derived to deal with the 3D trajectory-tracking problem of AUVs. Different from the above designs which only take the kinematics into consideration, kinematics and dynamics of AUVs are adopted in the process of the mathematical derivation of this proposed guidance law simultaneously. This proposed guidance law can effectively eliminate the nonlinearity of the kinematics and dynamics of the guided AUV and achieve a superior waypoint-tracking performance for any pre-arranged 3D trajectory. This proposed guidance law is prone to be implemented in the real calculator of AUVs due to the number of control gains and sensing states is few. Furthermore, the convergence of the tracking errors in positions and attitudes can be guaranteed to be zero easily in the absence of modeling uncertainties and environmental disturbances. This paper is organized as the following: Dynamics and kinematics of the guided AUV and the design objective are formulated in the Section 2. The proposed nonlinear PD guidance law for the guided AUV in 3D space is derived in Section 3. Simulation results with respect to two scenarios are given in Section 4 to verify the trajectory-tracking performance of the proposed guidance law. In Section 5, conclusions are made.

MATHEMATICAL MODEL OF AUVs AND DESIGN OBJECTIVE

Rigid-Body Dynamics

From Figure 1, the nonlinear equations of motion of the rigid-body AUV presented both in body-fixed and the earth-fixed reference frames with 6 DOF (degree of freedom), for global design are described as the following.

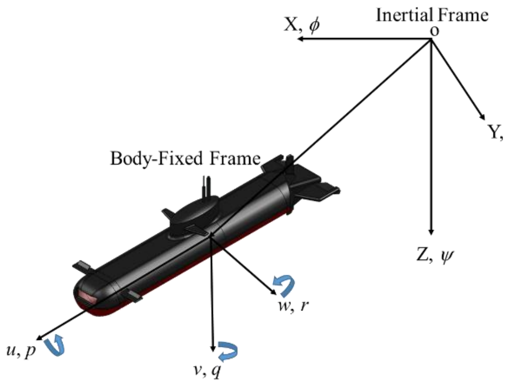

Fig. 1. The AUV geometry illustration

The Body-fixed vector representation of the controlled AUV is expressed as

$$\begin{cases} M\dot{B}+C(B)B+D(B)B+g(\eta)=\tau \\ \dot{\eta}=J(\eta)B \end{cases} \tag{1}$$

where

$$J(\eta)=\begin{bmatrix} c\psi c\theta & -s\psi c\varphi + c\psi s\theta s\varphi & s\psi s\varphi + c\psi c\varphi s\theta \\ s\psi c\theta & c\psi c\varphi + s\varphi s\theta s\psi & -c\psi s\varphi + s\theta s\psi c\varphi \\ -s\theta & c\theta s\varphi & c\theta c\varphi \end{bmatrix}$$

where $B=\begin{bmatrix} W & V \end{bmatrix}^T$ is the state vector, , including messages of velocity $V=\begin{pmatrix} u & v & w \end{pmatrix}$ and rotation angle rates $W=(p \quad q \quad r)$ of the controlled AUVs presented in the body coordinate. M is the inertia matrix, $C(B)$ is matrix of Coriolis and Centripetal term, $D(B)$ is damping matrix, $g(\eta)$ is vector of gravitational forces and moments, and τ is the guidance law vector.

For global design purpose, the nonlinear AUV dynamics in (1) is then reformulated as Earth-fixed vector representation in Euler-Lagrange form as

$$M_\eta(\eta)\ddot{\eta}+C_\eta(B,\eta)\dot{\eta}+D(\eta)\eta+g_\eta(\eta)=\tau_\eta \tag{2}$$

where $\eta=\begin{bmatrix} P & R \end{bmatrix}^T$ is the state vector, including messages of positions $P=\begin{pmatrix} x & y & z \end{pmatrix}$ and rotation angles $R=(\phi \quad \theta \quad \psi)$ of the controlled AUVs presented in the Earth coordinate. $M_\eta(\eta)=J^{-T}(\eta)MJ^{-1}(\eta)$ is the inertia matrix, $C_\eta(B,\eta)=J^{-T}(\eta)[C(B)-MJ^{-1}(\eta)\dot{J}(\eta)]J^{-1}(\eta)$ is matrix of Coriolis and Centripetal term and $\tau_\eta=\begin{bmatrix} F_x & F_y & F_z & \tau_\theta & \tau_\phi & \tau_\psi \end{bmatrix}$ is the guidance law vector.

where

$$M=\begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_x & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mx_G & -I_{yx} & I_y & -I_{yz} \\ -my_G & mx_G & 0 & -I_{zx} & -I_{zy} & I_z \end{bmatrix}$$

$$C(B)=\begin{bmatrix} 0_{3\times3} & A \\ B & C \end{bmatrix},\quad 0_{3\times3}=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$A=\begin{bmatrix} m(y_Gq+z_Gr) & -m(x_Gq-w) & -m(x_Gr+v) \\ -m(y_Gp+w) & m(z_Gr+x_Gp) & -m(y_Gr-u) \\ -m(z_Gp-v) & -m(z_Gq+u) & m(x_Gp+y_Gq) \end{bmatrix}$$

$$B=\begin{bmatrix} -m(y_Gq+z_Gr) & m(y_Gp+w) & m(z_Gp-v) \\ m(x_Gq-w) & -m(z_Gr+x_Gp) & m(z_Gq+u) \\ m(x_Gr+v) & m(y_Gr-u) & -m(x_Gp+y_Gq) \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & -I_{yx}q-I_{xz}p+I_zr & I_{yz}r+I_{xy}p-I_yq \\ I_{yz}q+I_{xz}p-I_zr & 0 & -I_{xz}r-I_{xy}q+I_xp \\ -I_{yz}r-I_{xy}p+I_yq & I_{xz}r+I_{xy}q-I_xp & 0 \end{bmatrix}$$

$$g(\eta)=\begin{bmatrix} (W-B)s\theta \\ -(W-B)c\theta s\varphi \\ -(W-B)c\theta c\varphi \\ -(y_GW-y_BB)c\theta c\varphi+(z_GW-z_BB)c\theta s\varphi \\ (z_GW-z_BB)s\theta+(x_GW-x_BB)c\theta c\varphi \\ -(x_GW-x_BB)c\theta s\varphi-(y_GW-y_BB)s\theta \end{bmatrix}$$

Design Objective

In this paper, the design objective is to develop one nonlinear PD type guidance law for the waypoint tracking problem of AUVs. Before deriving the guidance law τ_η, an error dynamics with a more compact form will be formulated as the following. In a given mission, positions (x_d, y_d, z_d), $d = 1, \ldots, n$, of the desired waypoints generally predefined; hence the position errors between the guided UAV and each waypoint can be expressed as follows:

$$e_p = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} = \begin{bmatrix} x - x_d \\ y - y_d \\ z - z_d \end{bmatrix} \tag{3}$$

As to the attitude errors for the controlled AUV tracking every single waypoint, they will be given as below. In this investigation, the guidance methodology used in attitude tracking design is light-of-sight (LOS) method hence LOS angles in vertical and horizontal plane should be calculated, respectively.

Define the vertical light-of-sight angle (VLOS) θ_d and horizontal light-of-sight angle (HLOS) ϕ_d as the following:

$$\theta_d = \tan^{-1}\left(\frac{y_d - y}{x_d - x}\right) \tag{4}$$

and

$$\phi_d = \tan^{-1}\left(\frac{z_d - z}{e_{2D}}\right) \tag{5}$$

where

$$e_{2D} = \sqrt{(x - x_d)^2 + (y - y_d)^2}$$

As to the desired rotation angle ψ_d, for the stability purpose, this angle will be maintained in the zero value as small as possible

$$\psi_d = 0 \tag{6}$$

Based on the above definitions, attitude errors between the controlled AUV and waypoints can be further defined as:

$$e_\phi = \phi - \phi_d \tag{7}$$

$$e_\theta = \theta - \theta_d \tag{8}$$

$$e_\psi = \psi - \psi_d \tag{9}$$

Combining (3), and (7-9), an overall tracking error vector can be expressed as an augmented vector form

$$\begin{aligned} e &= \eta - \eta_d \\ &= \begin{bmatrix} e_x & e_y & e_z & e_\theta & e_\phi & e_\psi \end{bmatrix}^T \end{aligned} \tag{10}$$

From (10), let the tracking error e be denoted as the system output, and τ_η in (2) is the system input; hence, the input-output relationship can be obtained by using feedback linearization method as the following:

Step 1: Differentiate tracking error in (10) with respect to time, and then it yields

$$\dot{e} = \dot{\eta} - \dot{\eta}_d \tag{11}$$

From equation (11), obviously, there is no input message τ_η can be found in the right hand side. According to input/output linearization theory, a further differentiation for (11) is necessary.

Step 2: Repeat the same mathematical operation as that in Step 1, then (11) becomes

$$\ddot{e} = \ddot{\eta} - \ddot{\eta}_d \tag{12}$$

Substituting equation (2) into (12), the second order nonlinear partial differential equation of the tracking error dynamics between AUVs and each desired waypoints is derived as below:

$$\begin{aligned} \ddot{e} = M_\eta(\eta)^{-1}\{&-C_\eta(B,\eta)\dot{\eta} - D_\eta(B,\eta)\dot{\eta} \\ &-g_\eta(\eta) + \tau_\eta - \ddot{\eta}_d\} \end{aligned} \tag{13}$$

The nonlinear waypoint-tracking problem of AUVs

Consider the error dynamics of the controlled AUV in (13). The design objective is to find a guidance law such that the following optimal performance can be achieved:

$$\min_{\tau_\eta(t)\in[0,\infty]} \left[e(t_f)^T e(t_f) \right] \tag{14}$$

Remark 1: *When $\phi - \phi_d \to 0$ and $\theta - \theta_d \to 0$, it means the guided AUV and each of the predefined waypoints is in the head-on condition. Therefore, the guided AUV will eventually hit the predefined waypoint if tracking errors are driven to zero before the controlled AUV crosses each predefined waypoint.* □

For achieving the above design objective and guarantee the tracking performance, an easy-to-implemented guidance law will be derived mathematically in the following section.

NONLINEAR GUIDANCE LAW

DESIGN OF AUVs

In this section, the waypoint-tracking problem of AUVs that is formulated in the above section will be solved with a theoretical design procedure.

By selecting a nonlinear PD guidance law for the system input τ_η of the guided AUV in (13) as the following:

$$\tau_\eta = M_\eta(\eta)\left\{C_\eta(B,\eta)\dot{\eta} + D_\eta(B,\eta)\dot{\eta} + g_\eta(\eta) + \ddot{\eta}_d + \Gamma_{PD}\right\} \quad (15)$$

where Γ_{PD} is a PD control term used to converge the tracking errors of positions and altitudes of the guided AUV to zero. Detailed formulations of Γ_{PD} and the error convergence derivation will be expressed later. Suppose the PD control term Γ_{PD} in (15) is selected as a vector form with adjustable parameters

$$\Gamma_{PD} = \begin{bmatrix}\gamma_{PD1} & \gamma_{PD2} & \gamma_{PD3} & \gamma_{PD4} & \gamma_{PD5} & \gamma_{PD6}\end{bmatrix}^T \quad (16)$$

where

$$\gamma_{PD1} = \ddot{x}_d + \alpha_1(\dot{x}_d - \dot{x}) + \alpha_2(x_d - x) \quad (17)$$

$$\gamma_{PD2} = \ddot{y}_d + \alpha_3(\dot{y}_d - \dot{y}) + \alpha_4(y_d - y) \quad (18)$$

$$\gamma_{PD3} = \ddot{z}_d + \alpha_5(\dot{z}_d - \dot{z}) + \alpha_6(z_d - z) \quad (19)$$

$$\gamma_{PD4} = \ddot{\theta}_d + \alpha_7(\dot{\theta}_d - \dot{\theta}) + \alpha_8(\theta_d - \theta) \quad (20)$$

$$\gamma_{PD5} = \ddot{\phi}_d + \alpha_9(\dot{\phi}_d - \dot{\phi}) + \alpha_{10}(\phi_d - \phi) \quad (21)$$

$$\gamma_{PD6} = \ddot{\psi}_d + \alpha_{11}(\dot{\psi}_d - \dot{\psi}) + \alpha_{12}(\psi_d - \psi) \quad (22)$$

and coefficients $\alpha_i > 0$, for $i = 1,2,\ldots,12$.

Substituting equations (16) and (15) into (12), a second order state-space formulation for the tracking error dynamics can be found as:

$$\ddot{e} + k_1\dot{e} + k_2 e = 0 \quad (23)$$

where

$$k_1 = \begin{bmatrix} \alpha_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \alpha_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & \alpha_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha_9 & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_{11} \end{bmatrix},$$

$$k_2 = \begin{bmatrix} \alpha_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \alpha_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & \alpha_8 & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha_{10} & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_{12} \end{bmatrix}$$

The coefficient $\alpha_i > 0$, for $i = 1,2,\ldots,12$ in equations (17)-(22) have to be selected so that the characteristic equation in (23) is a Hurwitz polynomial i.e., roots of (23) are all in the left-half complex plane. This implies that the overall tracking error dynamics (23) is asymptotically stable, and the tracking error e can be proven to converge to zero asymptotically with a convergence rate that depends on the choice of α_i.

Environmental disturbance: Current induced forces and moments

For verifying the guidance performance of this proposed method, the major environmental disturbance: ocean current, which always acts on AUVs should be discussed in the simulation process.

Current induced forces and torques can be represented in terms of the relative velocity.

$$V_r = V - V_c \quad (24)$$

where $V_c = \begin{pmatrix} u_c & v_c & w_c \end{pmatrix}$ is the current velocity vector. To obtain the sea current-induced forces and moment, we assume the body-frame current velocity is constant or at least slowly varying i.e., $\dot{V}_c = 0$ such that the following description is satisfied

$$\dot{V}_r = \dot{V} \quad (25)$$

From (1), the current induced forces and torques can be obtained as follows:

$$M\dot{V}_r + C(V_r)V_r = \tau_{\eta current} \quad (26)$$

From equation (1) are the current induced forces and torques and can be described as:

$$\tau_{current} = \begin{bmatrix} F_{xr} & F_{yr} & \omega_r \end{bmatrix}^T \quad (27)$$

The Earth-fixed representation of the current induced forces and torques $\tau_{currrnt}$ can be further expressed as $\tau_{currrnt}$ by using $J(\eta)$; hence the AUV dynamics adopted for the waypoint tracking simulation is

$$M_\eta(\eta)\ddot{\eta} + C_\eta(\nu,\eta)\dot{\eta} + g_\eta(\eta) = \tau_\eta + \tau_{\eta current} \quad (28)$$

SIMULATION RESULTS

To substantiate the performances of the proposed guidance law design, parameters for the inertia matrix M, matrix of Coriolis and Centripetal term $C(B)$, damping matrix $D(B)$ are given as Table 1.

Table 1 Nominal parameters of the controlled AUV

m	$188.43kg$	W	$1847kN$	B	$1847kN$
I_x	$68.41Nm^2$	I_y	$285.57Nm^2$	I_z	$141.32Nm^2$
I_{xy}	$0Nm^2$	I_{yz}	$0Nm^2$	I_{xz}	$0Nm^2$
x_G	$5cm$	y_G	$5cm$	z_G	$10cm$

An achievement requirement of tracking each waypoint for the guided AUV is practically defined as $\sqrt{e_x{}^2+e_y{}^2+e_z{}^2}<0.1\,(m)$.

In the following, there are two scenarios set up to test the waypoint-tracking performance of this proposed method.

Case 1: In Table 2, a scenairo with six waypoints is given. The initial point of the guided AUV is *P*=(x y z)=(0 0 0).

Table 2 Waypoints for Case 1

No.	Waypoints(X,Y,Z)(m)	No.	Waypoints(X,Y,Z)(m)
1 (Initial point)	(0,0,0)	4	(280,280,-30)
2	(20,20,-30)	5	(280,20,-30)
3	(120,280,-30)	6	(20, 20,-30)

Based on the proposed nonlinear PD guidance law in (15), the tracking performance of the guided AUV can be verified. Fig. 2 reveals the trajectory of the guided AUV after tracking six waypoints, and the corresponding waypoint tracking histories in positions and angles are plotted in Figs. 3-8, respectively. Obviously, from Figs. 3-5, this proposed guidance law can precisely guide the AUV to each waypoint, and tracking errors in position are always maintained within the achievement requirement $\sqrt{e_x{}^2+e_y{}^2+e_z{}^2}<0.1\,(m)$ even under the effects of the ocean current induced forces F_{xr}, F_{yr} and torque ω_r. The profiles of ocean current velocities are given in Figs. 15-17.

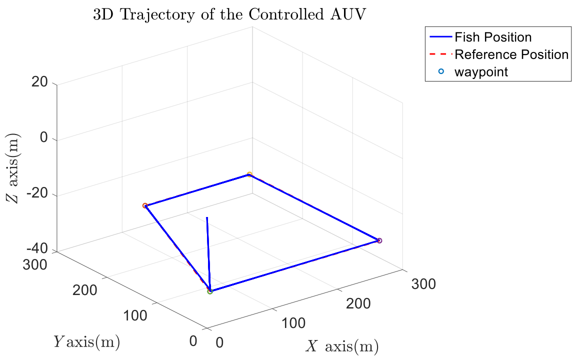

Fig. 2. Trajectory of the guided AUV for Case 1

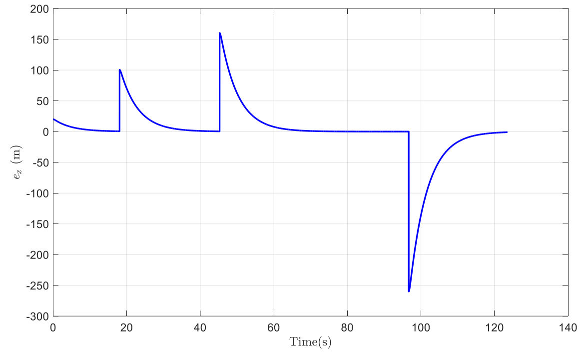

Fig. 3 History of the tracking error e_x in x axis

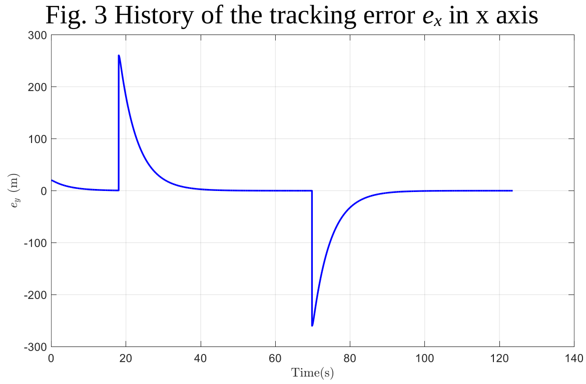

Fig. 4 History of the tracking error e_y in y axis

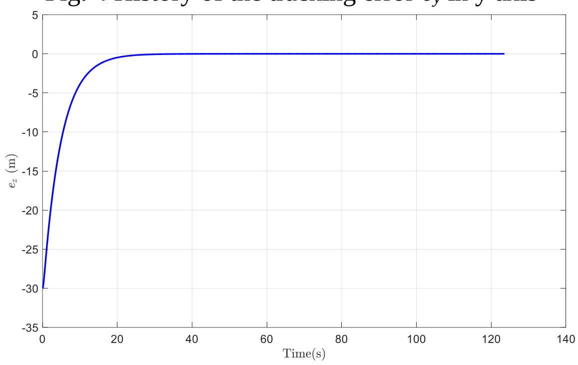

Fig. 5 History of the tracking error e_z in z axis

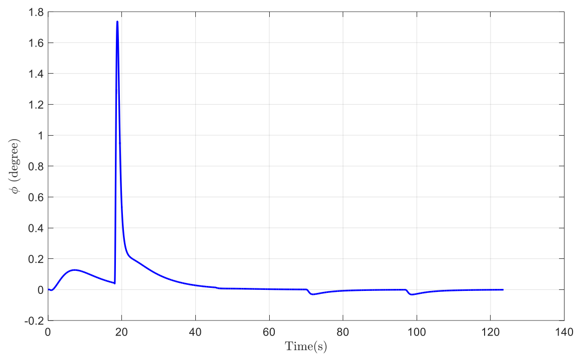

Fig. 6 History of the rotation angle ϕ

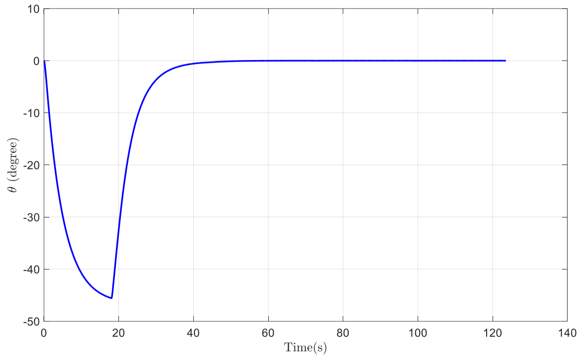

Fig. 7 History of the pitch angle θ

Control forces F_x, F_y, *and* F_z are shown in Figs. 9-11. Certainly, control forces to the guided AUV in three axes quickly converge to zero before approaching each waypoint. Similar properties reveal in applied torques τ_ϕ, τ_θ, and τ_ψ.

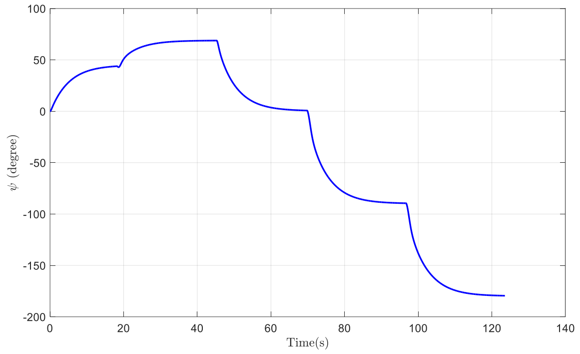

Fig. 8 History of the yaw angle ψ

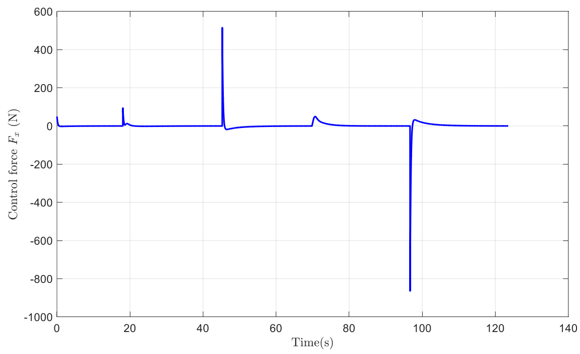

Fig. 9 History of the control force in X axis

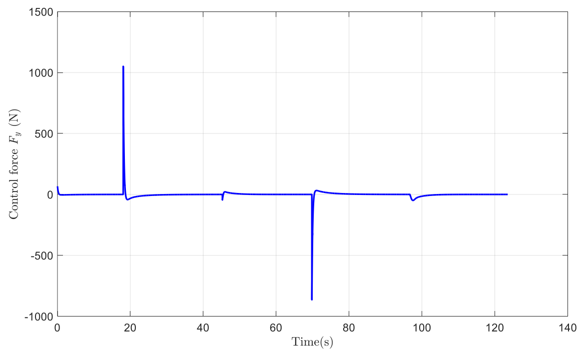

Fig. 10 History of the control force in Y axis

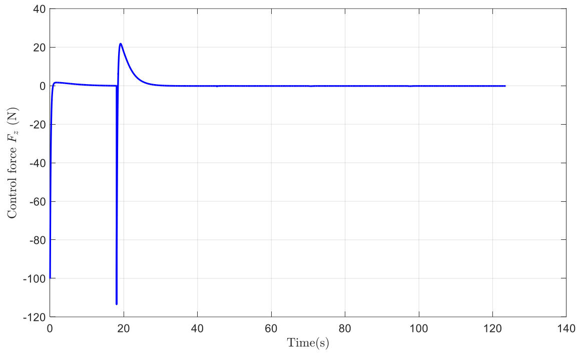

Fig. 11 History of the control force in Z axis

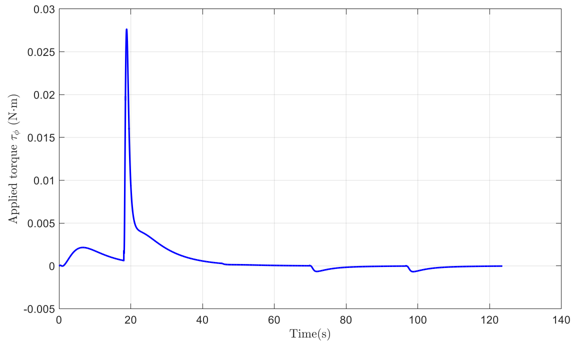

Fig. 12 History of the applied torque τ_ϕ

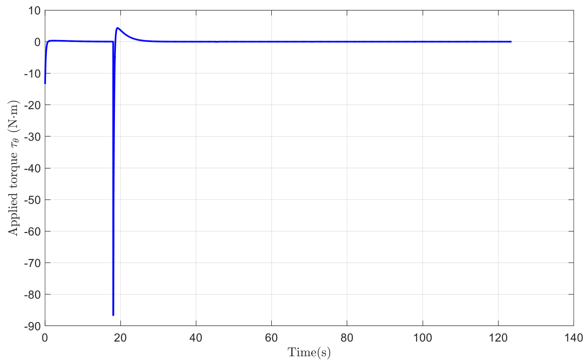

Fig. 13 History of the applied torque τ_θ

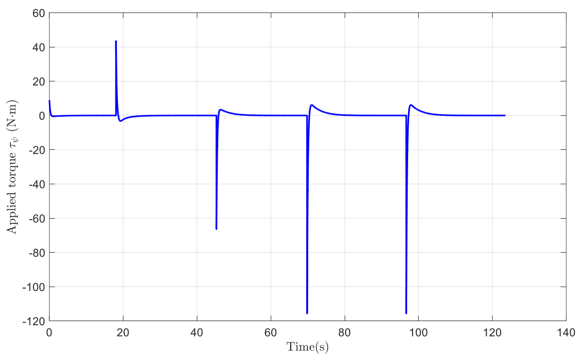

Fig. 14 History of the applied torque τ_ψ

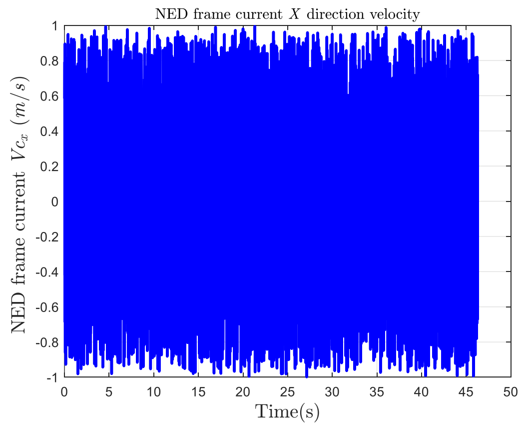

Fig. 15 The current velocity in X axis

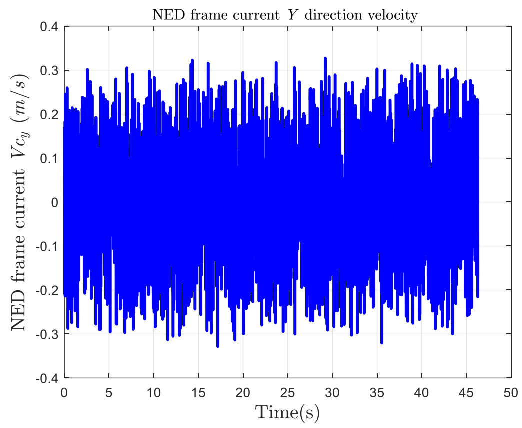

Fig. 16 The current velocity in Y axis

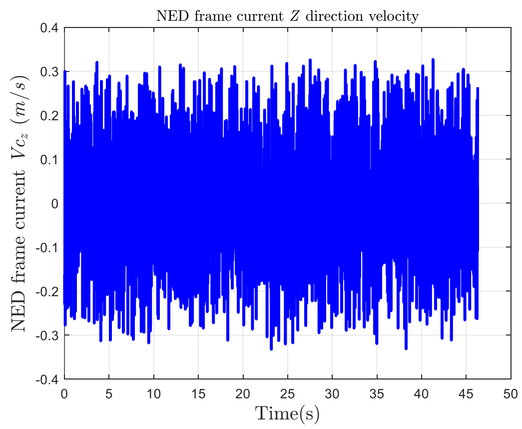

Fig. 17 The current velocity in Z axis

Case 2: A scenairo with a helix path generated by the following equation is adopted for the tracking performance verification of this proposed guidance law.

x=$rsin$(kn)
y=$rcos$(kn)
z=50-$3r$

where r=100, k=0.5, and n=1,..,50

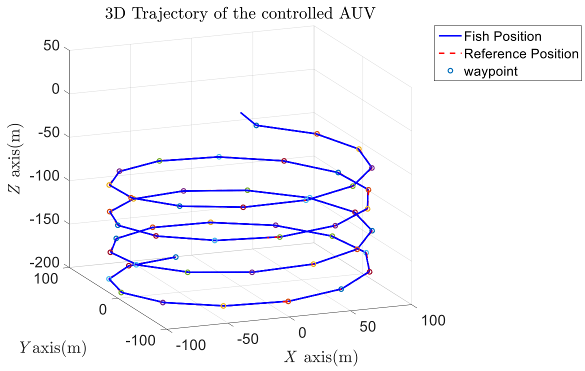

Fig. 18 Trajectory of the guided AUV for Case 2

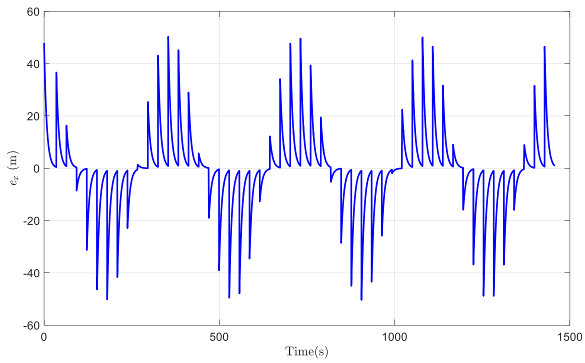

Fig. 19 History of the tracking error e_x in X axis

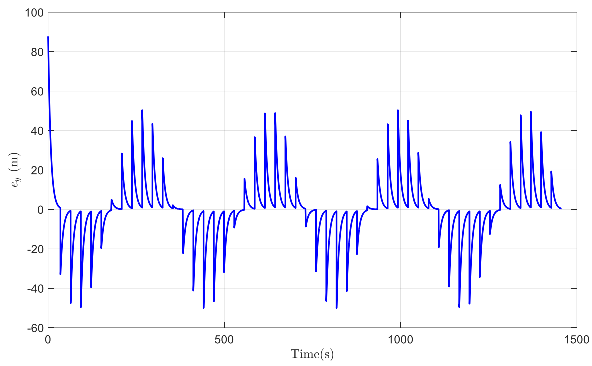

Fig. 20 History of tracking error e_y in Y axis

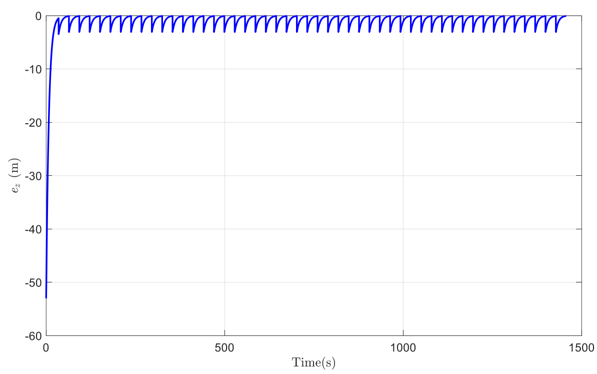

Fig.21 History of tracking error e_z in Z axis

3D trajectory of the controlled AUVs is shown in Fig. 18. The controlled AUV dives from the ocean surface (x, y, z)=(0,0,0) to the first waypoint (x_1, y_1, z_1) and then spirals down to a depth of -200m along a helix trajectory with a series of waypoints. Histories of tracking errors in positions are plotted in Figs. 19-21. Obviously, all tracking errors corresponding to each waypoint converge asymptotically to near zero in the presence of ocean disturbances.

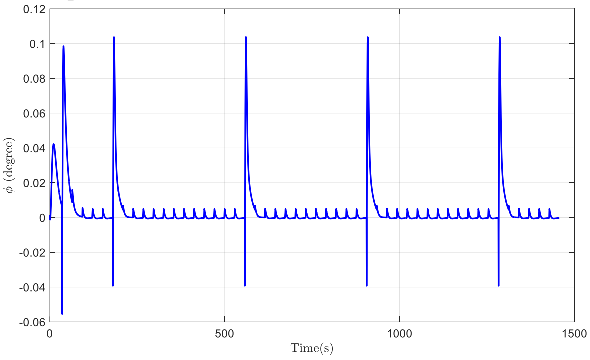

Fig. 22 History of the rotation angle ϕ

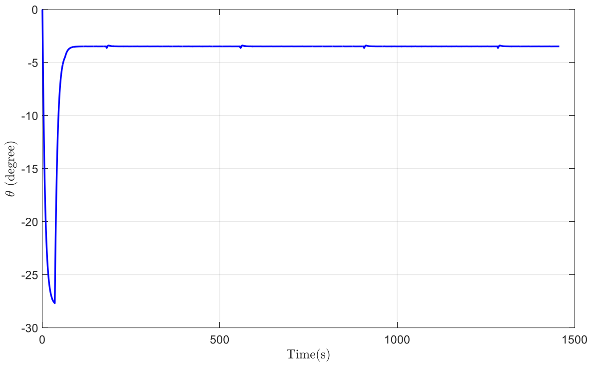

Fig. 23 History of the pitch angle θ

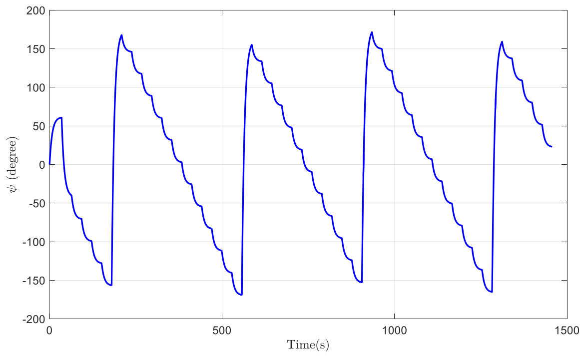

Fig. 24 History of the yaw angle ψ

Attitude angles ϕ, θ, and ψ are exhibited in Figs. 22-24. For stabilizing the AUV, the roll angle ϕ is controlled to be zero. The pitch angle θ maintains a 3° diving angle from the initial position to the final destination. As the heading angle ψ, a periodic variation in angle can be found due to the spiral tracking behavior of the controlled AUV. Control forces and applied torques of this performance test is illustrated in Figs. 25-30. Certainly, all control commands $(F_x, F_y, F_z, \tau_\phi, \tau_\theta, \tau_\psi)$ converges to zero before approaching each waypoint, and a slight torque is used to stablize the roll angle ϕ.

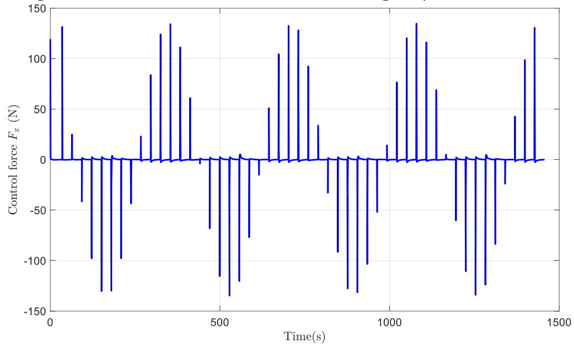

Fig. 25 History of the control force F_x in X axis

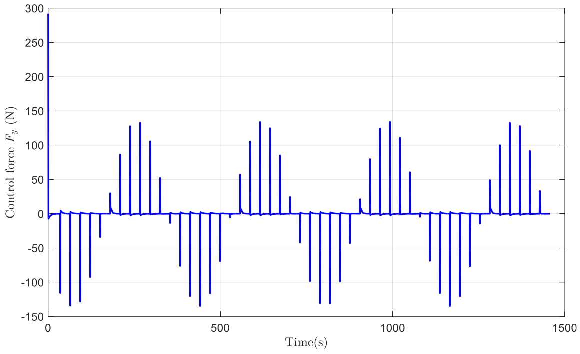

Fig. 26 History of the control force F_y in Y axis

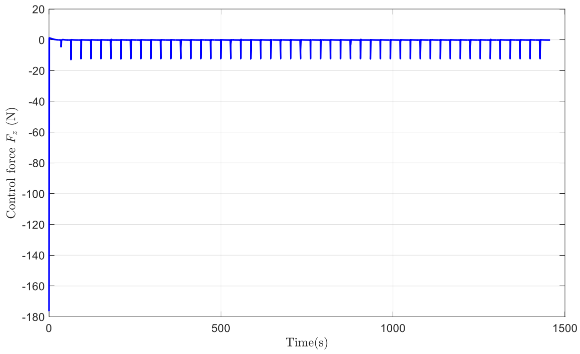

Fig. 27 History of the control force , F_z in Z axis

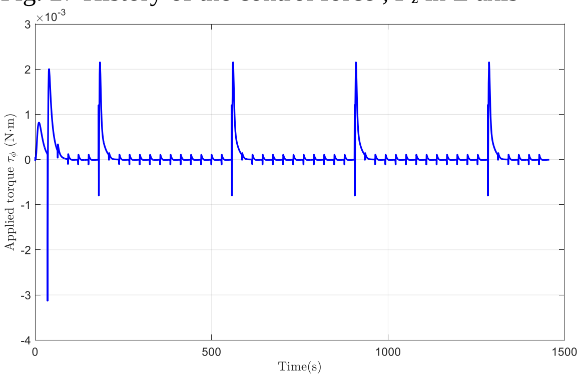

Fig. 28 History of the applied control torque τ_ϕ

In this simulation, figures of ocean environmnetal disturbances including ocean current induced forces and torques $\tau_{currrnt}$ in Eq. (28) are omitted for saving pages.

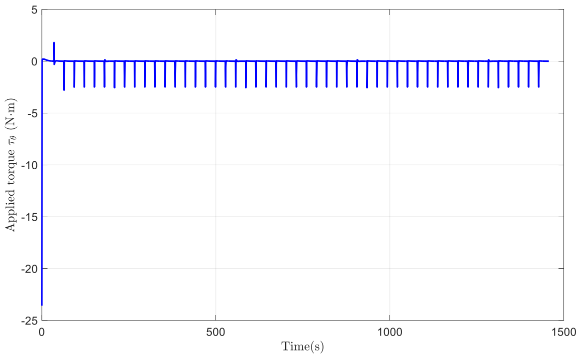

Fig. 29 History of the applied torque τ_θ

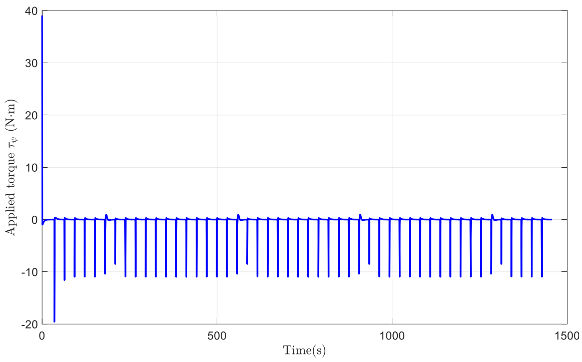

Fig. 30 History of the applied torque τ_ψ

CONCLUSIONS

A nonlinear guidance law with a PD type control structure and a global tracking ability is developed successfully for autonomous underwater vehicles. By using the coordinate transformation of tracking error dynamics, this guidance law guarantees the global stability and the convergence of tracking errors when the guided AUV tracks each predefined waypoint. Besides, tracking errors can be proven to asymptotically converge to zero in absence of ocean disturbances. From the simulation results, it is easy to find out that this proposed nonlinear guidance law exhibits an excellent tracking ability for no matter the simple scenario or the complex scenario. Furthermore, this proposed method is still capable of delivering satisfactory tracking performances when random ocean currents appear in the AUV's dynamics.

ACKNOWLEDGMENT

This work was supported by National Science Council, Taiwan, R. O. C., under the Grant NSC104-2628-E-006-012-MY3.

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自主式水下載具非線性導引律設計

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摘要

此研究針對無人水下載具提出一 3D 非線性導航設計。此導航設計的特色在於一具全域穩定性質的非線性最佳 PD 型式導引律於此研究中可被推導出來。針對水下載具導航問題，要求得一具三度空間全域穩定的非線性最佳化導引律相當不容易。因為一高度非線性之偏微分方程的解需先被求出。藉此求出解才有機會進一步建構非線性最佳化導引律。此設計出之非線性最佳化導引律可讓水下載具採最省能量及最短航程的方式航行至任一事先安排之導航點且可保證軌跡誤差為最小。同時水下載具於受控期間之系統的全域穩定性質也可以被保證。