International Journal of Automation and Computing 11(3), June 2014, 299-307
DOI: 10.1007/s11633-014-0792-7

Adaptive Tracking Control of an Autonomous Underwater Vehicle

Basant Kumar Sahu Bidyadhar Subudhi

Centre for Industrial Electronics and Robotics, Department of Electrical Engineering, National Institute of Technology, Rourkela, India

Abstract: This paper presents the trajectory tracking control of an autonomous underwater vehicle (AUV). To cope with parametric uncertainties owing to the hydrodynamic effect, an adaptive control law is developed for the AUV to track the desired trajectory. This desired state-dependent regressor matrix-based controller provides consistent results under hydrodynamic parametric uncertainties. Stability of the developed controller is verified using the Lyapunov′s direct method. Numerical simulations are carried out to study the efficacy of the proposed adaptive controller.

Keywords: Autonomous underwater vehicle (AUV), adaptive control law, regressor matrix, Lyapunov′s stability, path following.

1 Introduction

Over the last two decades, research on control of autonomous underwater vehicles (AUVs) has become an important topic due to their wide applications in security patrols, search and rescue in hazardous environments, etc.[1−3]. In military missions, a group of AUVs are required to maintain a specific formation for an area coverage and reconnaissance. Remotely operated vehicles (ROVs) and AUVs are directly involved in exploitation of resources located at deep oceanic environment[4]. AUVs are also used in risky and hazardous operations such as bathymetric surveys, oceanographic observations, recovery of lost manmade objects and ocean floor analysis.

The trajectory planning and tracking of an AUV is an important research topic. During traversing in a computed path, an AUV provides real-time data to be compared with the designed model[5]. The path is planned by considering two points such as start point and a destination point with a velocity field, where the path is to be traversed within a minimum time[6, 7]. The optimum path is efficiently generated using path parameterization, cost function techniques and minimum expenditure of energy[8]. The coordinated path following problem of marine craft was proposed in [9], where the path following situation was discussed based on the convergence of geometric errors at the origin of each vehicle. The problem of path planning was solved based on fast marching algorithm in [10], where the path tracking algorithm was designed by assuming the AUV to maneuver on a fixed depth. The AUVs were given a task of mine counter measure (MCM) based on synthetic aperture sonar (SAS) data collected at sea[11]. The path following problem was solved by getting inspiration from biological agents in [12]. This bio-inspired model in horizontal plane was capable of generating real time smooth forward and angular velocities. The path following and trajectory tracking problems were solved by a backstepping approach using a special type of kinematics which was developed by Lyapunov′s direct method, and then it was extended to solve the dynamic problem in [13]. The problem of trajectory planning and tracking control was solved by using error dynamics of AUV in the horizontal plane in [14], in which the closed loop tracking controller was developed using backstepping techniques. An adaptive controller was also developed for controlling the nonholonomic mobile robot in [15, 16], where the learning method on neutral network is used to design the robust adaptive controller. In [17], a fuzzy adaptive linearized controller with backstepping-like feedback was used to control the wheeled mobile robot for tracking of the desired trajectories. An adaptive sliding mode controller was used to control the uncertainties accompanied by the camera mounted on the nonholonomic dynamic mobile robot in [18]. A nonlinear iterative sliding mode incremental feedback controller that was developed to track an AUV along the desired trajectories in the horizontal plane is described in [19]. An adaptive neural network controller based on dynamic surface control (DSC) and minimal learning parameters (MLP) was proposed in [20]. The problem of trajectory tracking of AUV was solved in [21] by using sliding mode controller combined with line of sight (LOS) and cross track error methods. The adaptive controller along with radial basis function neural network (RBF-NN) was employed for controlling AUVs to follow the desired trajectories in [22]. A static output feedback controller was proposed in [23] for controlling an AUV to track along the desired trajectory. A virtual vehicle concept that is used to develop the backstepping controller for controlling unmanned underwater vehicle (UUV) to track along the desired trajectory was presented in [24]. A feedback controller based on LOS in the presence of oceanic current disturbances was developed in [25] to control the AUVs for tracking the desired trajectories. A region boundary adaptive controller developed for trajectory tracking of AUV was presented in [26], where the entire boundary was united by the use of multiplicative potential energy functions. In [27], a backstepping controller with a LOS guidance system was used to control an AUV to track the desired trajectory in the presence of ocean

Regular Paper
Manuscript received June 16, 2013; revised July 24, 2013
This work was supported by Naval Research Board, Defense Research Development Organization (DRDO), Government of India (No. DNRD/05/4003/NRB/160).

current, in which the unknown parameters were estimated by using parameter rejection techniques. A new frame work for object detection and tracking method of an AUV was presented in [28]. This controller was designed for a vision-based AUV which carries a forward looking sonar. In [29], a backstepping adapting controller was developed for an AUV to track the desired path. The stability of the developed controller was proved by using a Lyapunov′s criterion.

Path planning of different autonomous agents such as marine crafts, mobile robots and AUVs has been reported in literature. Tracking of an AUV along a desired trajectory is an important task. It is difficult to develop a controller for an AUV in the dynamic environment where hydrodynamic uncertainties exist. Under these difficulties, the focus of this paper is to develop a trajectory tracking control law of the AUV. The contribution of this paper lies in the development of an adaptive controller such that the AUV can track the desired trajectory in the dynamic environment in the presence of uncertainties owing to hydrodynamic parameters.

In this work, we assume that while moving in a horizontal plane, the dynamic behavior of an AUV is similar to that of an under-actuated surface vessel. Also the orientation of the AUV is similar to that of the surface vessel. It is intended to design a control law such that the AUV can track a desired trajectory accordingly.

In the development of the controller for an under-actuated AUV, we consider four degrees of freedom (DOF) for simplicity. We propose an adaptive controller using a regressor matrix consisting of unknown parameters. The stability of the developed control law is verified using Lyapunov′s stability criterion. From the numerical simulations presented, it can be seen that the proposed controller is efficient in providing appropriate adaptive control action to force the AUV to follow the desired trajectory in the presence of hydrodynamic parameter uncertainties.

Some challenges involved with this approach, as compared to some existing approaches[14, 19], are as follows. The dynamics of the AUV is nonlinear and uncertain, and the effects of Coriolis, gravitational and damping factors in six degrees of freedom increase the mathematical complexity. Thus, designing an adaptive control law and its implementation are challenging. To ensure the stability of the proposed controller by choosing the Lyapunovs function is also difficult.

The rest of the paper is organized as follows. Section 2 presents the problem statement. AUV kinematics and dynamics are discussed in Section 3. The development of a new adaptive control law based on regressor approach for the AUV to achieve tracking of a desired trajectory is developed in Section 4. In this section, the stability of the developed adaptive control law is verified by using Lyapunov′s stability criterion. To verify the efficiency of the proposed control law, simulation studies are made and results analyses are provided in Section 5. Conclusions are presented in Section 6.

2 Problem statement

Starting from any arbitrary point in the space, the AUV must asymptotically converge to the desired trajectory after a certain time. In other words, the actual trajectory travelled by the AUV should coincide with the desired one, i.e., the tracking errors between the positions of the desired and actual trajectories should be zero, namely

$$\lim_{t\to\infty} |\eta - \eta_d| = 0 \tag{1}$$

where $\eta = [x, y, z, \phi, \theta, \psi]^{\rm T}$ is the position and orientation vector in the inertial frame; x, y, z are the coordinates of position, and $\phi,\ \theta,\ \psi$ are orientations in the longitudinal, transversal and vertical axes, respectively. $\eta_d = [x_d, y_d, z_d, \phi_d, \theta_d, \psi_d]^{\rm T}$ is the position and orientation vector of the desired trajectory; x_d, y_d, z_d are the coordinates of the desired position, and $\phi_d,\ \theta_d,\ \psi_d$ are orientations in the desired longitudinal, transversal and vertical axes, respectively.

3 AUV kinematics and dynamics

The AUV dynamics contains highly nonlinear and coupled terms which make the mathematical modeling difficult. The forces and moments of a simple AUV in three dimensions is presented in Fig. 1.

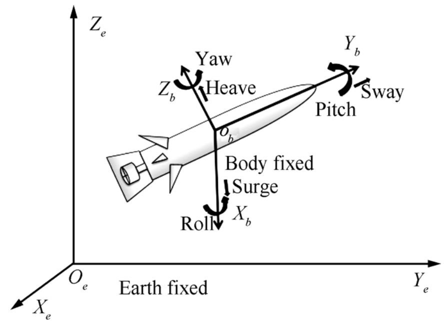

Fig. 1 Schematic presentation of an AUV with different frame of references

Consider the motion of an AUV in 6-DOF. Define the following vector[30]:

$$\begin{aligned} \nu &= [u, v, w, p, q, r]^{\rm T} \\ \tau &= [X, Y, Z, K, M, N]^{\rm T} \end{aligned} \tag{2}$$

where ν is the velocity vector in the body-fixed frame, u, v and w denote linear velocities; p, q, r are angular velocities; X, Y, Z are forces; K, M, N denote moments. τ is the vector of forces and moments acting on the AUV in the body-fixed frame.

The dynamic equation of motion can be expressed as

$$M(\eta)\ddot{\eta} + C(\eta, \dot{\eta})\dot{\eta} + D(\eta, \dot{\eta})\dot{\eta} + g(\eta) = \tau. \tag{3}$$

The kinematic equation of AUV is given by

$$\dot{\eta} = J(\eta)\,\nu \tag{4}$$

where $M(\eta)$ is the inertia matrix including added mass, $C(\eta, \dot{\eta})$ is the matrix of Coriolis and centripetal terms including the added mass. $D(\eta, \dot{\eta})$ denotes the hydrodynamic damping and lift matrix, $g(\eta)$ is the vector of gravitational forces and moments, and $J(\eta)$ is the velocity transformation matrix between AUV and earth fixed frames.

This transformation matrix $J(\eta)$ can be obtained as

$$J(\eta)=\begin{bmatrix} J_1(\eta) & 0_{3\times3} \\ 0_{3\times3} & J_2(\eta)\end{bmatrix} \tag{5}$$

where

$$J_1(\eta)=\begin{bmatrix} \mathrm{c}\psi\mathrm{c}\theta & -\mathrm{s}\psi\mathrm{c}\phi+\mathrm{c}\psi\mathrm{s}\theta\mathrm{s}\phi & \mathrm{s}\psi\mathrm{s}\phi+\mathrm{c}\psi\mathrm{c}\phi\mathrm{s}\theta \\ \mathrm{s}\psi\mathrm{c}\theta & \mathrm{c}\psi\mathrm{c}\phi+\mathrm{s}\phi\mathrm{s}\theta\mathrm{c}\psi & -\mathrm{c}\psi\mathrm{s}\phi+\mathrm{s}\theta\mathrm{s}\psi\mathrm{c}\phi \\ -\mathrm{s}\theta & \mathrm{c}\theta\mathrm{s}\phi & \mathrm{c}\theta\mathrm{c}\phi \end{bmatrix} \tag{6}$$

$$J_2(\eta)=\begin{bmatrix} 1 & \mathrm{s}\phi\mathrm{t}\theta & \mathrm{c}\phi\mathrm{t}\theta \\ 0 & \mathrm{c}\phi & -\mathrm{s}\phi \\ 0 & \dfrac{\mathrm{s}\phi}{\mathrm{c}\theta} & \dfrac{\mathrm{c}\phi}{\mathrm{c}\theta}\end{bmatrix} \tag{7}$$

where $\mathrm{s}(\cdot)=\sin(\cdot)$, $\mathrm{c}(\cdot)=\cos(\cdot)$, $\mathrm{t}(\cdot)=\tan(\cdot)$.

Assumption 1. Due to asymmetric body structure of the AUV, deriving a control law is very difficult. For sake of convenience, the following assumptions are made.

1) Center of mass (CM) and center of buoyancy (CB) coincide with each other.

2) Mass distribution all over the body is homogeneous.

3) The hydrodynamic terms of higher order as well as pitch and role motions are negligible.

4 Path following control law

The AUV dynamics given in (3) has parameter uncertainties in damping factors. It is intended to compensate these uncertainties. Therefore, an adaptive control law is developed to obtain consistent performance of the AUV by estimating the uncertain parameters. The adaptation mechanism is used to adjust the parameters in the control law. The proposed adaptive controller is designed such that it forces the AUV to track the desired trajectory in the presence of parameter uncertainties. For this, we define a regressor matrix

$$Y=Y(\eta,\dot{\eta},\dot{\eta}_d,\ddot{\eta}_d)$$

such that

$$M\ddot{\eta}_d+C(\eta,\dot{\eta})\dot{\eta}_d+D(\eta,\dot{\eta})\dot{\eta}_d+g(\eta)=Y(\eta,\dot{\eta},\dot{\eta}_d,\ddot{\eta}_d)\alpha \tag{8}$$

where $\eta_d=[x_d,y_d,z_d,\phi_d,\theta_d,\psi_d]^{\mathrm{T}}$ is the position and orientation vector of the desired trajectory in the inertial frame.

Consider the control law in the following form:

$$\tau=Y\hat{\alpha}-K_Ds \tag{9}$$

where $Y\hat{\alpha}$ is the feed forward term, K_Ds is a simple propositional differential (PD) term. K_D is a positive definite gain matrix and the error vector s is defined as

$$\begin{aligned} s&=e_\nu+\Lambda e_p\\ e_p&=\eta-\eta_d\\ e_\nu&=\nu-\nu_d \end{aligned} \tag{10}$$

$\Lambda=$ positive definite matrix

$$\dot{\hat{\alpha}}=-\Gamma Y^{\mathrm{T}}s \tag{11}$$

where Γ is the positive definite symmetric matrix. It is chosen in such a way that the tuning law provides convergent characteristics.

It will be shortly proved that, the proposed parameter adaptation law given in (11) is able to drive the AUV in the desired trajectory and the stability of the AUV system is ensured.

The structure of the proposed adaptation control law is shown in Fig. 2.

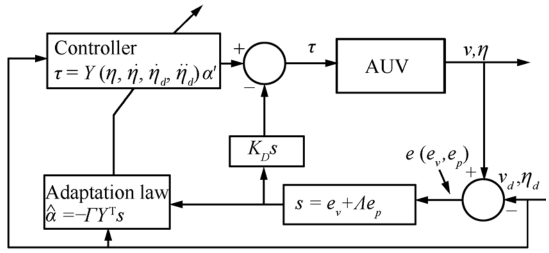

Fig. 2 Structure of the proposed adaptation control law

The stability of the proposed adaptive control law is proved by using Lyapunov′s stability criterion as described below. Choose a Lyapunov candidate function, $V(t)$ satisfies (12) and is given by (13)

$$\begin{cases} V(t):\mathbf{R}^n\rightarrow\mathbf{R}\ \text{such that}\\ V(t)\geqslant 0,\text{if and only if } t=0 \text{ (positive definite)}\\ \dot{V}(t)=\dfrac{\mathrm{d}}{\mathrm{d}t}V(t)\leqslant 0,\\ \qquad \text{if and only if } t=0 \text{ (negative definite).}\end{cases} \tag{12}$$

We will prove that the system is asymptotically stable in the sense of Lyapunov if (12) is satisfied.

Proof (Stability of the proposed control law). Let $V(t)$ be a Lyapunov candidate function and be given by

$$V(t)=\frac{1}{2}\left[s^{\mathrm{T}}Ms+\tilde{\alpha}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}\right]=V_1(t)+V_2(t) \tag{13}$$

where $V_1(t)=\frac{1}{2}s^{\mathrm{T}}Ms$ and $V_2(t)=\frac{1}{2}\tilde{\alpha}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}$.

Taking derivative of (13) gives

$$\dot{V}(t)=\dot{V}_1(t)+\dot{V}_2(t). \tag{14}$$

Analysis of first term of (14):

$$\dot{V}_1(t)=s^{\mathrm{T}}M\dot{s}+\frac{1}{2}s^{\mathrm{T}}\dot{M}. \tag{15}$$

Substituting (10) into (15) and referring to [31], one can get

$$\dot{V}_1(t)=s^{\mathrm{T}}M(\ddot{\eta}-\ddot{\eta}_d)+\frac{1}{2}s^{\mathrm{T}}\dot{M}s \tag{16}$$

where $s=\dot{\eta}-\dot{\eta}_d$.

Substituting the value of $M(\eta)\ddot{\eta}$ from (3) into (15) and solving for $\dot{V}_1(t)$, one obtains

$$\dot{V}_1(t)=s^{\mathrm{T}}\left(\tau-C\dot{\eta}-D\dot{\eta}-g-M\ddot{\eta}_d\right)+\frac{1}{2}s^{\mathrm{T}}\dot{M}s. \tag{17}$$

But $\dot{\eta} = s + \dot{\eta}_d$,

$$\dot{V}_1(t) = s^{\mathrm{T}}(\tau - C\dot{\eta}_d - D\dot{\eta}_d - g - M\ddot{\eta}_d - (C+D)s) + \frac{1}{2}s^{\mathrm{T}}\dot{M}s \tag{18}$$

or

$$\dot{V}_1(t) = s^{\mathrm{T}}(\tau - M\ddot{\eta}_d - C\dot{\eta}_d - D\dot{\eta}_d - g) + \frac{1}{2}s^{\mathrm{T}}\left(\dot{M} - 2(C+D)\right)s. \tag{19}$$

One can easily verify that for an AUV, $\dot{M} - 2(C+D)$ is a skew-symmetric matrix. Substituting the system dynamics of AUV given in (3) into (19), one has

$$\dot{V}_1(t) = s^{\mathrm{T}}(\tau - M\ddot{\eta}_d - C\dot{\eta}_d - D_d\dot{\eta} - g). \tag{20}$$

Analysis of second term of (14):

The second term of (14) can be rewritten as

$$V_2(t) = \frac{1}{2}\tilde{\alpha}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}, \quad \tilde{\alpha} = \hat{\alpha} - \alpha \tag{21}$$

where $\dot{\tilde{\alpha}} = \dot{\hat{\alpha}}$, as $\alpha =$ constant definite vector.

The first derivative of (21) is

$$\dot{V}_2(t) = \dot{\hat{\alpha}}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}. \tag{22}$$

Therefore

$$\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) = s^{\mathrm{T}}(\tau - M\ddot{\eta}_d - C\dot{\eta}_d - D_d\dot{\eta} - g) + \dot{\hat{\alpha}}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}. \tag{23}$$

Using (8) in (23) one obtains

$$\dot{V}(t) = s^{\mathrm{T}}(\tau - Y\tilde{\alpha}) + \dot{\hat{\alpha}}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}. \tag{24}$$

Substituting the controller input $\tau = Y\hat{\alpha} - K_D s$ into (24) and solving (24) gives

$$\dot{V}(t) = s^{\mathrm{T}}Y\tilde{\alpha} - s^{\mathrm{T}}K_D s + \dot{\hat{\alpha}}^{\mathrm{T}}\Gamma^{-1}\tilde{\alpha}. \tag{25}$$

Substituting $\dot{\hat{\alpha}} = -\Gamma Y^{\mathrm{T}} s$ into (25), we can obtain

$$\dot{V}(t) = -s^{\mathrm{T}}K_D s \leqslant 0. \tag{26}$$

Equation (26) satisfies the Lyapunov′s stability criterion for AUV dynamics with a stable controller. Hence the proposed adaptive control law (9) yields a stable closed system. □

Considering the model of AUV in 4-DOF for simplicity, (8) can be presented as

$$M\ddot{\eta}_d + D(\eta, \dot{\eta})\dot{\eta}_d = \tau \tag{27}$$

or

$$\begin{bmatrix} m_{11} & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & 0 \\ 0 & 0 & 0 & m_{44} \end{bmatrix} \begin{bmatrix} \dot{u}_d \\ \dot{v}_d \\ \dot{w}_d \\ \dot{r}_d \end{bmatrix} + \begin{bmatrix} d_{11} & 0 & 0 & 0 \\ 0 & d_{22} & 0 & 0 \\ 0 & 0 & d_{33} & 0 \\ 0 & 0 & 0 & d_{44} \end{bmatrix} \begin{bmatrix} u_d\,|u_d| \\ v_d\,|v_d| \\ w_d\,|w_d| \\ r_d\,|r_d| \end{bmatrix} = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \\ \tau_r \end{bmatrix} \tag{28}$$

where $\tau = [\tau_x, \tau_y, \tau_z, \tau_r]^{\mathrm{T}}$.

Let the reference trajectory of the AUV be defined as

$$\dot{x}_d = u_d, \ \dot{y}_d = v_d, \ \dot{z}_d = w_d, \ \dot{\psi}_d = r_d. \tag{29}$$

Equation (28) can be rewritten in a simplified form as

$$\begin{aligned} m_{11}\dot{u}_d + d_{11}\,|u_d|\,u_d &= \tau_x \\ m_{22}\dot{v}_d + d_{22}\,|v_d|\,v_d &= \tau_y \\ m_{33}\dot{w}_d + d_{33}\,|w_d|\,w_d &= \tau_z \\ m_{44}\dot{r}_d + d_{44}\,|r_d|\,r_d &= \tau_r. \end{aligned} \tag{30}$$

Equations (30) can be expressed in a matrix form as

$$Y(\nu_d, \dot{\nu}_d)\alpha = \tau \tag{31}$$

where

$$\nu_d = [u_d, v_d, w_d, r_d]^{\mathrm{T}} \tag{32}$$

$$Y(\nu_d, \dot{\nu}_d) = \begin{bmatrix} \dot{u}_d & |u_d|\,u_d & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \dot{v}_d & |v_d|\,v_d & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dot{w}_d & |w_d|\,w_d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \dot{r}_d & |r_d|\,r_d \end{bmatrix}$$

where $Y(\nu_d, \dot{\nu}_d)$ denotes the regressor matrix and α is defined as

$$\alpha = [m_{11}, d_{11}, m_{22}, d_{22}, m_{33}, d_{33}, m_{44}, d_{44}]^{\mathrm{T}}. \tag{33}$$

Using the regressor matrix $Y(\nu_d, \dot{\nu}_d)$, the AUV model (27) can be expressed in a linear parametric form. The derivation of the regressor matrix of a high-DOF is very tedious. Hence, only four DOFs are considered for simplicity. For real-time realization, the regressor matrix is to be computed in each control cycle; also the computation of each parameter of the matrix is performed in each iteration[32]. The regressor matrix is a state dependent matrix. The elements of this matrix contain velocity and acceleration terms which are computed in each iteration of the control cycle.

5 Results and discussions

The proposed adaptive control algorithm was applied to a four DOF AUV model as given in (27) which is rewritten as

$$M\ddot{\eta}_d + D(\eta, \dot{\eta})\dot{\eta}_d = \tau \tag{34}$$

$$\eta_d = [x_d, y_d, z_d, \psi_d]^{\mathrm{T}} \tag{35}$$

where

$$M = \mathrm{diag}\{m_{11}, m_{22}, m_{33}, m_{44}\}$$
$$D(\eta, \dot{\eta}) = \mathrm{diag}\{d_{11}, d_{22}, d_{33}, d_{44}\}.$$

Equation (28) can be rewritten as

$$\tau = Y(\eta, \dot{\eta}, \dot{\eta}_d, \ddot{\eta}_d)p \tag{36}$$

where

$$Y(\eta,\dot\eta,\dot\eta_d,\ddot\eta_d)=$$

$$\begin{bmatrix} \ddot x_d & |\dot x_d|\,\dot x_d & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \ddot y_d & |\dot y_d|\,\dot y_d & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddot z_d & |\dot z_d|\,\dot z_d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \ddot\psi_d & \left|\dot\psi_d\right|\dot\psi_d \end{bmatrix} \quad (37)$$

$$p=[m_{11},d_{11},m_{22},d_{22},m_{33},d_{33},m_{44},d_{44}]^{\rm T}. \quad (38)$$

To verify the efficacy of the proposed control law, numerical simulations are carried out. Consider various desired trajectories and conditions as described next.

Case 1. Desired circular path. We consider a desired circular path as

$$x_d=10\sin(0.01t)$$
$$y_d=10\cos(0.01t)$$
$$z_d=10,\ \psi_d=\frac{\pi}{3}. \quad (39)$$

It is ensured that the derivatives at least second order of (39), i.e., $\dot x_d,\dot y_d,\dot z_d,\dot\psi_d,\ddot x_d,\ddot y_d,\ddot z_d,\ddot\psi_d$ exist. The parameters of the AUV which are necessary are considered and given in Table 1.

Next, we present the results obtained as follows.

Figs. 3 (a) and (b) show the planner and spatial views of the actual and reference positions when the AUV intended to track a circular path as given in (39). From these figures, it is observed that after 10 s, the AUV tracked the desired trajectory (Fig. 4 (a)).

The comparison of the desired and actual positions as well as orientations of the AUV in the earth fixed inertial frame of reference is shown in Fig. 4 (b). From this figure, it is observed that the actual and desired positions matched with each other in 10 s.

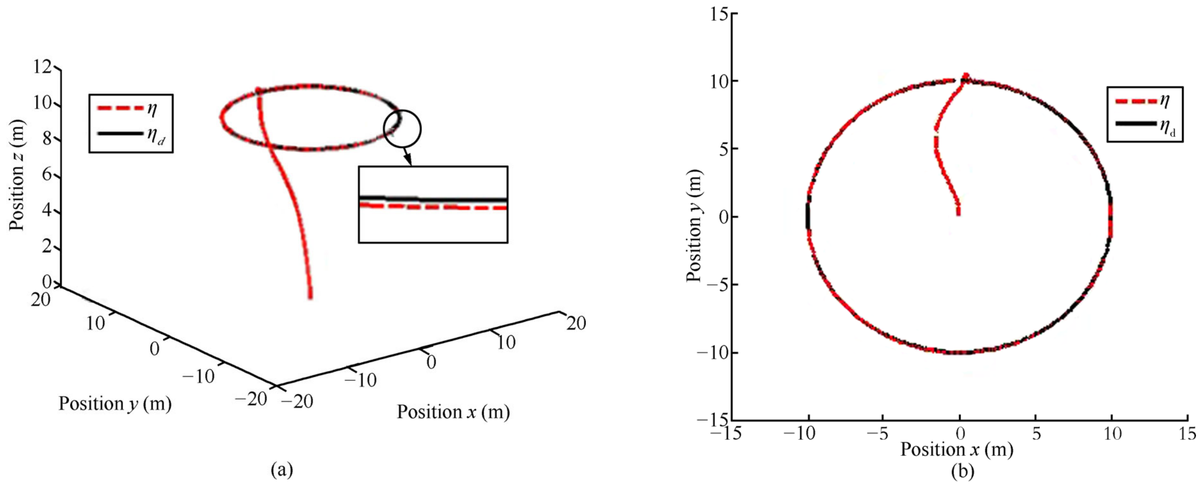

Fig. 3 Circular trajectory tracking of AUV with reference path and actual path: (a) Spatial view; (b) Planner view

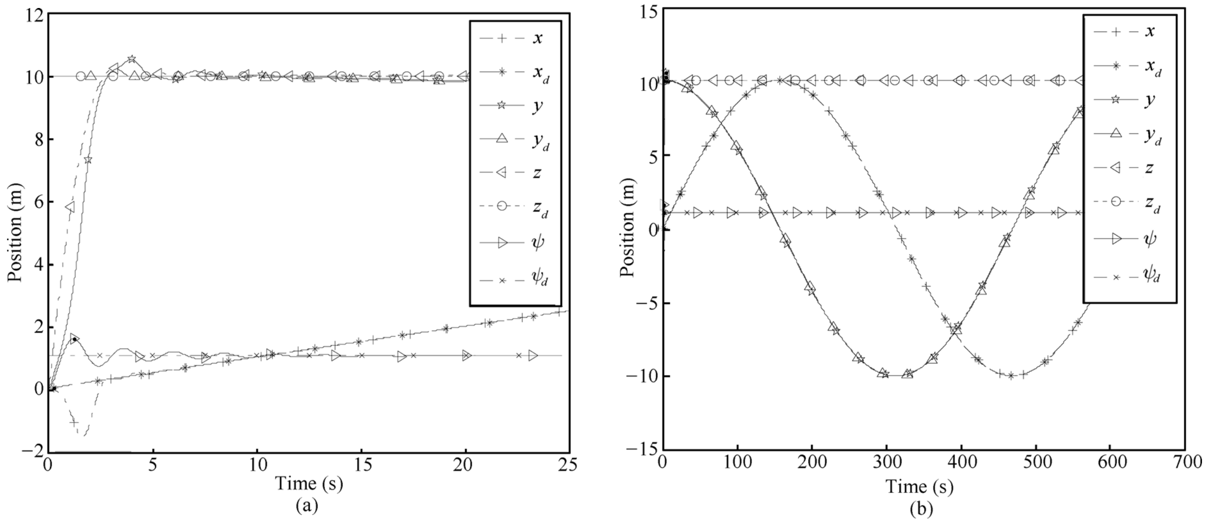

Fig. 4 Actual position and reference position in circular path for (a) 25 s and (b) 700 s, respectively

Table 1 Parameters of AUV used for simulation

Mass (kg)	Damping coefficients (kg/s)	Other parameters
$m_{11}=100$	$d_{11}=10{+}222.15\lvert u\rvert$	$K_D=\mathrm{diag}\{10,20,50,10\}$
$m_{22}=109$	$d_{22}=400.18\lvert v\rvert$	$\Lambda=\mathrm{diag}\{50,10,20,20\}$
$m_{33}=125$	$d_{33}=10{+}225.76\lvert w\rvert$	$\Gamma=\mathrm{diag}\{200,10,20,$
$m_{44}=28.8$	$d_{44}=1.80{+}11.78\lvert r\rvert$	$0,0,0,10,10\}$

Fig. 5 presents the comparison of the desired and the actual linear velocities as well as angular velocities of the AUV. From this result, it is observed that the desired and the actual velocities matched with each other.

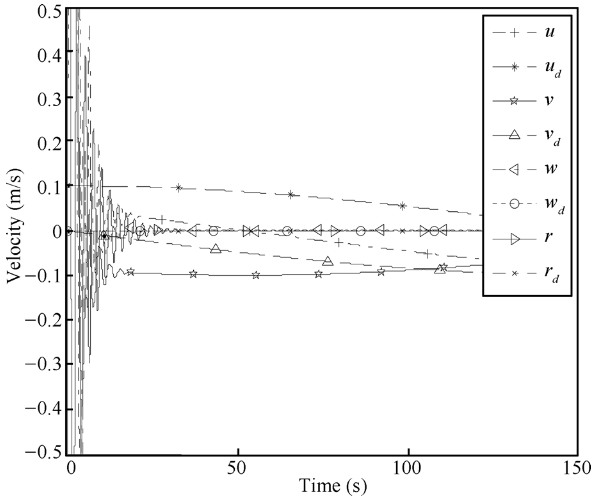

Fig. 5 Actual velocity and desired velocity in circular path

Fig. 6 depicts the position errors in the x, y, z, ψ directions. From this result, it is observed that the position errors converged to zero. Thus the proposed controller steered the AUV to track the desired path accurately.

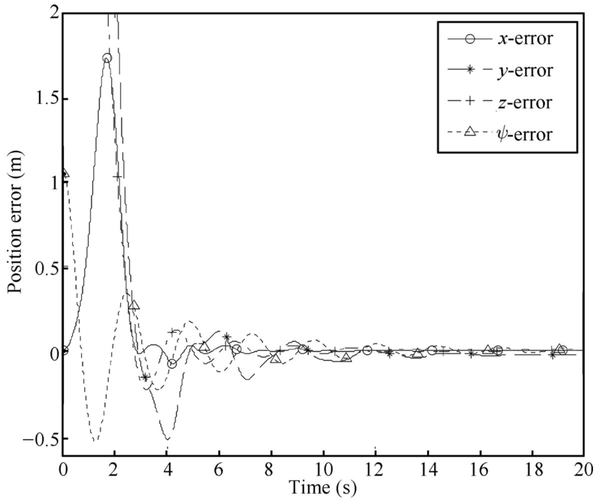

Fig. 6 Position errors in circular path

The errors between desired and actual linear velocities as well as angular velocities of the AUV in the body fixed frame of reference are shown in Fig. 7. From this figure, it is found that the velocity errors converged to zero, i.e., the actual and the desired states (both positions and velocities) of the AUV closely matched with each other.

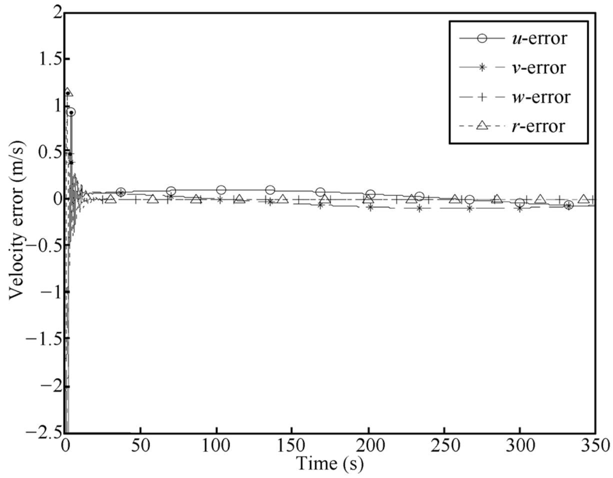

Fig. 7 Velocity errors in circular path

Fig. 8 shows the forces and torques applied to the AUV. From this figure, it is observed that in the early period, the AUV required some force and torque to start its initial journey. After 20 s, the forces and torques asymptotically converged to zero, indicating that the linear and angular accelerations became zero, i.e., the linear and angular velocities became constants. Hence, the AUV tracked the desired trajectory smoothly after 20 s.

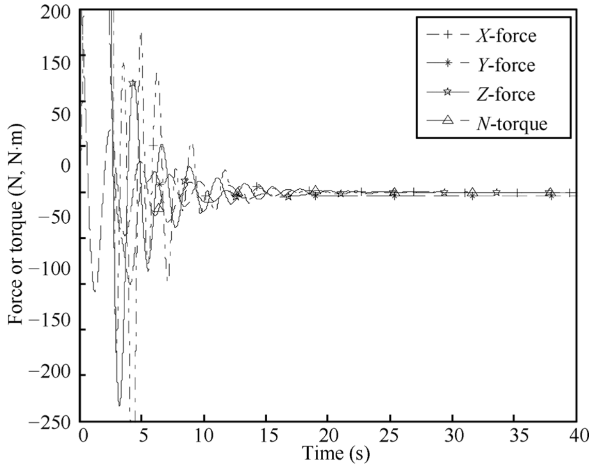

Fig. 8 Forces and torques in circular path

Case 2. Desired spiral path. Next we consider a spiral path in the space as

$$\begin{aligned} x_d &= 10\sin(0.01t)\\ y_d &= 10\cos(0.01t)\\ z_d &= t,\ \psi_d=\frac{\pi}{3}. \end{aligned} \tag{40}$$

As in the case of circular path, for the spiral path the derivatives up to the second order, i.e., $\dot{x}_d,\dot{y}_d,\dot{z}_d,\dot{\psi}_d,\ddot{x}_d,\ddot{y}_d,\ddot{z}_d,\ddot{\psi}_d$ are also necessary. The other parameters such as m_{11}, m_{22}, m_{33}, m_{44}, d_{11}, d_{22}, d_{33}, d_{44}, K_D, Λ and Γ are given in Table 1.

Fig. 9 shows the spiral path followed by the AUV. From this figure, it is clear that by using the proposed control law, the AUV tracked the desired trajectory. The desired as well as actual positions and velocities are shown in Figs. 10 (a),

(b) and Fig. 11, respectively. From these figures, it is clear that the desired positions and velocities matched with the actual positions and velocities of the AUV, respectively.

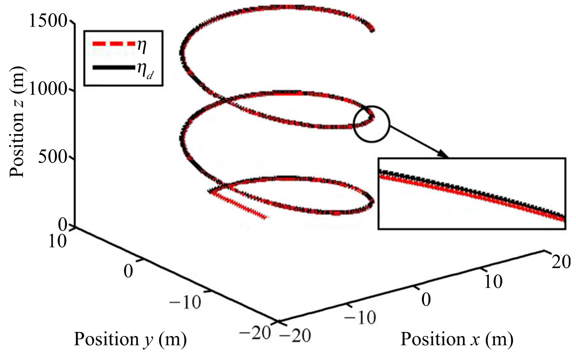

Fig. 9 Spiral trajectory tracking of AUV

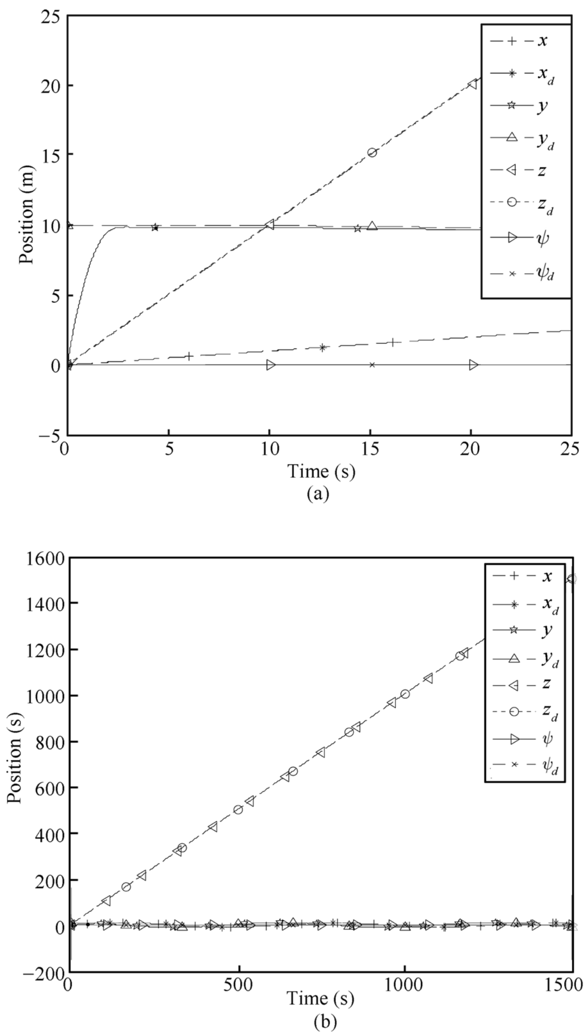

Fig. 10 Actual position and reference position in circular path for (a) 25 s and (b) 1500 s, respectively

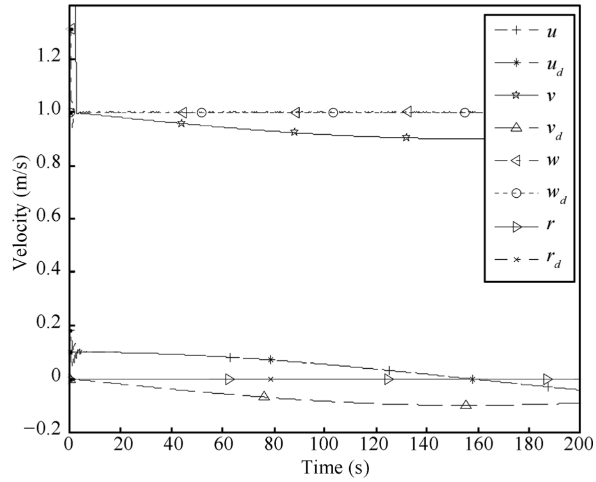

Fig. 11 Actual velocity and desired velocity in spiral path

Figs. 12 and 13 show the position and velocity errors, respectively. From these figures, it is observed that the position and velocity errors tended to zero in 10 s from the beginning.

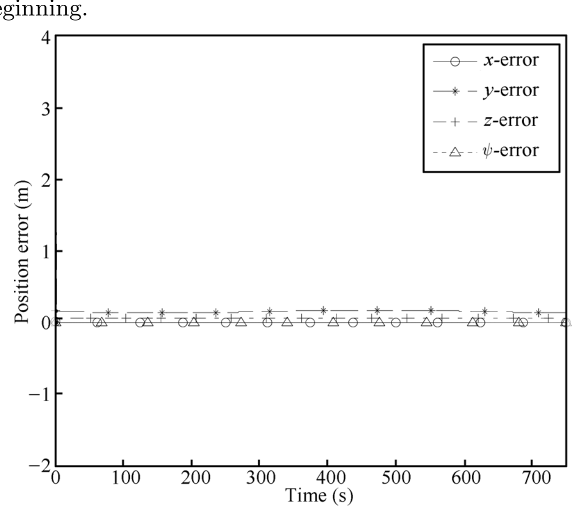

Fig. 12 Position errors in spiral path

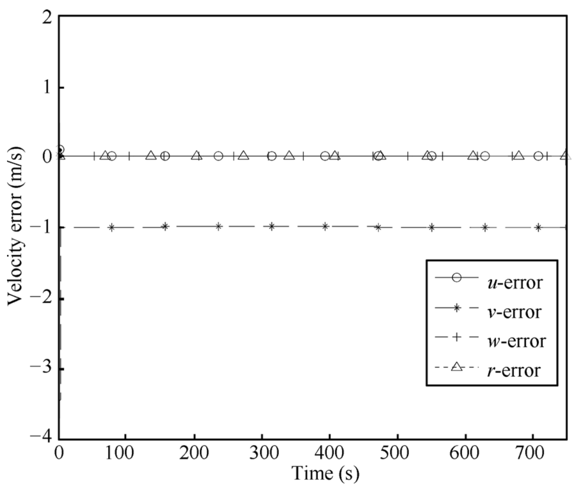

Fig. 13 Velocity errors in spiral path

Fig. 14 shows the forces and torques applied to the AUV. From this figure, it is observed that in the beginning stage of motion of the AUV, the forces and torques had some definite values and these were asymptotically tending to zero. This shows that at the early stage the AUV accomplished acceleration, which then gradually tended to zero. So the AUV tracked the desired trajectory with a constant velocity smoothly.

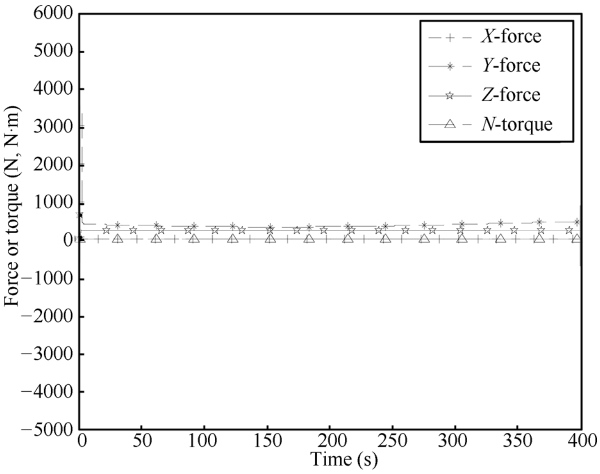

Fig. 14 Forces and torques

6 Conclusions

In this paper, a new adaptive control law for trajectory tracking of AUV moving in space is addressed. The adaptive control law is developed with estimation of uncertain parameters associated with the hydrodynamic damping coefficients. This law is used to generate appropriate control for the AUV to track the desired trajectories. The stability of the control law is verified using Lyapunov′s direct method. By comparing the desired positions and velocities with the actual positions and velocities, respectively, it is found that all the errors are converge to zero quickly. From the numerical simulation results, the efficacy and accuracy of the developed control law are verified.

Acknowledgement

The authors wish to thank the editor and reviewers for their suggestions to improve the quality of the paper.

References

[1] D. J. Stilwell, B. E. Bishop. Platoons of underwater vehicles. *IEEE Control Systems Magazine*, vol. 20, no. 6, pp. 45–52, 2000.

[2] R. W. Beard, J. Lawton, F. Y. Hadaegh. A coordination architecture for spacecraft formation control. *IEEE Transactions on Control Systems Technology*, vol. 9, no. 6, pp. 777–790, 2001.

[3] D. P. Scharf, F. Y. Hadaegh, S. R. Ploen. A survey of spacecraft formation flying guidance and control (Part I): Guidance. In *Proceedings of 2003 American Control Conference*, IEEE, Denver, Colorado, USA, vol. 2, pp. 1733–1739, 2003.

[4] Y. S. Kim, J. Lee, S. K. Park, B. H. Jeon, P. M. Lee. Path tracking control for underactuated AUVs based on resolved motion acceleration control. In *Proceedings of the 4th International Conference on Autonomous Robots and Agents*, IEEE, Wellington, New Zealand, pp. 342–346, 2009.

[5] R. N. Smith, Y. Chao, P. P. Li, D. A. Caron, B. H. Jones, G. S. Sukhatme. Planning and implementing trajectories for autonomous underwater vehicles to track evolving ocean processes based on predictions from a regional ocean model. *International Journal of Robotics Research*, vol. 29, no. 12, pp. 1475–1479, 2010.

[6] B. Garau, M. Bonet, A. Álvarez, S. Ruiz, A. Pascual. Path planning for autonomous underwater vehicles in realistic oceanic current fields: Application to gliders in the western Mediterranean sea. *Journal of Maritime Research*, vol. 6, no. 2, pp. 5–21, 2009.

[7] D. Kruger, R. Stolkin, A. Blum, J. Briganti. Optimal AUV path planning for extended missions in complex, fast-flowing estuarine environments. In *Proceedings of IEEE International Conference on Robotics and Automation*, IEEE, Roma, Italy, pp. 4265–4270, 2007.

[8] D. Kruger, R. Stolkin, A. Blum, J. Briganti. Optimal AUV path planning for extended missions in complex, fast-flowing estuarine environments. In *Proceedings of IEEE International Conference on Robotics and Automation*, IEEE, Rome, Italy, pp. 4265–4270, 2007.

[9] J. Ghommam, O. Calvo, A. Rozenfeld. Coordinated path following for multiple underactuated AUVs. In *Proceedings of OCEANS MTS/IEEE Kobe Techno-Ocean*, IEEE, Kobe, Japan, pp. 1–7, 2008.

[10] H. Bo, R. Hongge, Y. Ke, H. Luyue, R. Chunyun. Path planning and tracking for autonomous underwater vehicles. In *Proceedings of IEEE International Conference on Information and Automation*, IEEE, Zhuhai/Macau, China, pp. 728–733, 2009.

[11] D. P. Williams. On optimal AUV track-spacing for underwater mine detection. In *Proceedings of IEEE International Conference on Robotics and Automation*, IEEE, Alaska, USA, pp. 4755–4762, 2010.

[12] Y. Zhao, D. Zhu. A bio-inspired kinematic model of AUV tracking control for ocean current. In *Proceedings of IEEE International Conference on Computer Science and Automation Engineering (CSAE)*, IEEE, Shanghai, China, pp. 478–482, 2011.

[13] X. B. Xiang, L. Lapierre, C. Liu, B. Jouvencel. Path tracking: Combined path following and trajectory tracking for autonomous underwater vehicles. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, IEEE, San Francisco, USA, pp. 3558–3563, 2011.

[14] F. Repoulias, E. Papadopoulos. Planar trajectory planning and tracking control design for underactuated AUVs. *Ocean Engineering*, vol. 34, no. 11–12, pp. 1650–1667, 2007.

[15] N. Sadegh, R. Horowitz. Stability and robustness analysis of a class of adaptive controllers for robotic manipulators. *International Journal of Robotics Research*, vol. 9, no. 3, pp. 74–92, 1990.

[16] O. Mohareri, R. Dhaouadi, A. B. Rad. Indirect adaptive tracking control of a nonholonomic mobile robot via neural networks. *Neurocomputing*, vol. 88, pp. 54–66, 2012.

[17] D. Chwa. Fuzzy adaptive tracking control of wheeled mobile robots with state-dependent kinematic and dynamic disturbances. *IEEE Transactions on Fuzzy Systems*, vol. 20, no. 3, pp. 587–593, 2012.

[18] F. Yang, C. L. Wang. Adaptive tracking control for uncertain dynamic nonholonomic mobile robots based on visual servoing. *Journal of Control Theory and Applications*, vol. 10, no. 1, pp. 56–63, 2012.

[19] L. Wang, H. M. Jia, L. J. Zhang, H. B. Wang. Horizontal tracking control for AUV based on nonlinear sliding mode. In *Proceedings of IEEE International Conference on Information and Automation (ICIA)*, IEEE, Shenyang, China, pp. 460–463, 2012.

[20] B. B. Miao, T. S. Li, W. L. Luo. A DSC and MLP based robust adaptive NN tracking control for underwater vehicle. *Neurocomputing*, vol. 111, pp. 184–189, 2013.

[21] F. D. Gao, C. Y. Pan, Y. Y. Han, X. Zhang. Nonlinear trajectory tracking control of a new autonomous underwater vehicle in complex sea conditions. *Journal of Central South University*, vol. 19, no. 7, pp. 1859–1868, 2012.

[22] X. Q. Bian, J. J. Zhou, Z. P. Yan, H. N. Jia. Adaptive neural network control system of path following for AUVs. In *Proceedings of the Southeastcon*, IEEE, Orlando, FL, USA, pp. 1–5, 2012.

[23] B. Subudhi, K. Mukherjee, S. Ghosh. A static output feedback control design for path following of autonomous underwater vehicle in vertical plane. *Ocean Engineering*, vol. 63, pp. 72–76, 2013.

[24] W. Zhang, D. Xu, M. L. Tan, C. L. Wang, Z. P. Yan. Trajectory tracking control of underactuated UUV for underwater recovery. In *Proceedings of the 2nd International Conference on Instrumentation, Measurement, Computer, Communication and Control (IMCCC)*, IEEE, Harbin, China, pp. 386–391, 2012.

[25] W. Caharija, K. Y. Pettersen, J. T. Gravdahl, E. Borhaug. Path following of underactuated autonomous underwater vehicles in the presence of ocean currents. In *Proceedings of the 51st IEEE Conference on Decision and Control (CDC)*, IEEE, Maui, HI, USA, pp. 528–535, 2012.

[26] Z. H. Ismail, B. M. Mokhar, M. W. Dunnigan. Tracking control for an autonomous underwater vehicle based on multiplicative potential energy function. In *Proceedings of IEEE OCEANS*, IEEE, Yeosu, Korea, pp. 1–6, 2012.

[27] X. G. Xia, Y. Ying, Z. W. Guang. Path-following in 3D for underactuated AUV in the presence of ocean current. In *Proceedings of the 5th IEEE International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)*, IEEE, Hong Kong, China, Korea, pp. 788–791, 2013.

[28] T. D. Zhang, L. Wan, W. J. Zeng, Y. R. Xu. Object detection and tracking method of AUV based on acoustic vision. *China Ocean Engineering*, vol. 26, no. 4, pp. 623–636, 2012.

[29] L. Lapierre, B. Jouvencel. Robust nonlinear path-following control of an AUV. *IEEE Journal of Oceanic Engineering*, vol. 33, no. 2, pp. 89–102, 2008.

[30] T. I. Fossen. *Guidance and Control of Ocean Vehicles*, New York: John Wiley & Sons, 1994.

[31] J. J. E. Slotine, W. Li. *Applied Nonlinear Control*, Englewood Cliffs, NJ: Prentice-Hall, 1991.

[32] A. C. Huang, M. C. Chien. *Adaptive Control of Robot Manipulators: A Unified Regressor-free Approach*, Singapore: World Scientific Publishing Company, 2010.

Basant Kumar Sahu is a Ph. D. candidate at the Department of Electrical Engineering, National Institute of Technology (NIT) Rourkela, India. He received his M. Sc. degree in electronics from Berhampur University, Odisha in 2004 and M. Tech. in electronics design technology from Tezpur Central University, India in 2008. He was awarded the Canadian Commonwealth Scholarship by Canadian Bureau for International Education for pursuing a short term research proposal in University of Saskatchewan, Canada in 2012.

His research interests include nonlinear control, underwater vehicle control, robotics and intelligence control.

E-mail: basant.ece@gmail.com

Bidyadhar Subudhi received his B. Eng. degree in electrical engineering from National Institute of Technology (NIT) Reginal Engineering College (REC), India in 1988, M. Tech. in control and instrumentation from Indian Institute of Technology Delhi (IIT) in 1993 and Ph. D. degree in control system engineering from University of Sheffield, UK in 2003. He was a post-doctoral research fellow in the Department of Electrical & Computer Engineering, National University of Singapore (NUS), Singapore during May–November 2005. He was a visiting professor in University of Saskatchewan, Canada during May–June 2009 and also at Asian Institute of Technology (AIT) Bangkok during Jan–May 2013. He is a professor at the Department Electrical Engineering, National Institute of Technology (NIT) Rourkela, India. He is currently coordinator of Centre of Excellence, Renewable Energy System, Centre of Excellence, Industrial Electronics & Robotics and head of Computer Centre at NIT Rourkela. He is also the principal investigator in several research projects funded by Defense Research Development Organization (DRDO), Council of Scientific and Industrial Research (CSIR) and Department of Science and Technology (DST), including an international cooperation project under the UK India Education Research Initiative (UKIERI) scheme. He has published 40 journal papers in prestigious journals such as IEEE Transactions, IET and Elsevier and presented 70 research papers in many international conferences both in India and abroad. He has edited one book and contributed 3 book chapters. He chaired a number of technical sessions in international conferences. He is a fellow of the IET (UK) and senior member of IEEE (USA). He is a regular reviewer of *IEEE Transaction on Systems, Man, & Cybernetics, Power Delivery, Control System Technology*, and *Neural Networks and Automatic Control.*

His research interests include system identification and adaptive control, networked control system, control of flexible and under water robots, control of renewable energy systems, estimation and filtering with application to power system.

E-mail: bidyadhar@nitrkl.ac.in (Corresponding author)