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Trajectory Tracking Control of Underactuated AUV in the Presence of Ocean Currents

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Abstract

This paper addresses the trajectory tracking problem of underactuated autonomous underwater vehicles (AUVs) in the presence of ocean currents on the horizontal plane. The tracking control problem is reduced the problem of stabilizing the nonlinear tracking error system to two separate problems. The backstepping technique is applied to design tracking controller, and the conditions of control gains are derived such that the AUV can track a reference AUV. Simulations results show the effectiveness of the proposed trajectory tracking controller.

Keywords: *AUV, trajectory tracking control, backstepping, Lyapunov method*

1. Introduction

Autonomous Underwater Vehicles (AUVs) depicted in Figure 1, are playing a crucial role in exploration and exploitation of resources located at deep oceanic environments. They are employed in risky missions such as oceanographic observations, military applications, recovery of lost man-made objects, etc [1]. AUVs present a challenging control problem since most of them are underactuated they have less actuator than state variables to be tracked, imposing nonintegrable acceleration constraints. However, AUVs' models are highly nonlinear, making control problem a hard task.

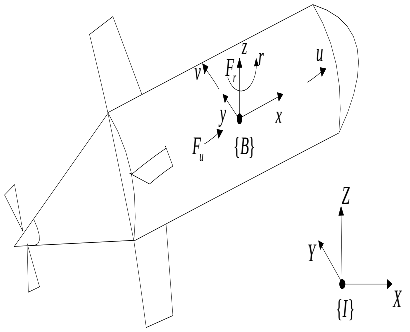

Figure1. The Underactuated AUV Model

Recently, trajectory tracking control problem of underactuated AUVs has received a lot of attention for the control community. Trajectory tracking issue refers to the case where the vehicle tracks a reference trajectory generated by a suitable virtual vehicle a geometric path on which a time law is specified. Note that when moving on a horizontal plane,

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AUVs present similar dynamic behavior to underactuated surface vessels [2]. A high gain based, local exponential tracking result was obtained by applying the recursive technique for the standard chain form systems [3]. Based on Lyapunov's direct method and passivity approach, two constructive tracking solutions were proposed for an underactuated surface ship [4]. The trajectory tracking problems of underactuated systems were solved based on cascaded systems by many scholars. A full state feedback control law that make the underactuated ship follow a straight line is developed using a cascaded approach [5]. A new cascade approach for global κ-exponential tracking of underactuacted ships was derived [6]. Based on sliding mode with eigenvalue decomposition and cascaded theory, a control scheme for a line of sight guidance law of an underactuated AUV was proposed [7]. The control problem of tracking a desired continuous trajectory for an AUV in the presence of gravity, buoyancy and fluid dynamic forces and moments was studied [8]. The hybrid control law is developed by combining sliding mode (SMC) and classical proportional-integral-derivative (PID) control methods for the tracking control of an underactuated AUV [9]. A adaptive switching control combined with a nonlinear Lyapunov-based tracking control are applied to solve the problem of position trajectory tracking control for an underactuated AUV in the presence of possibly large modeling parametric uncertainty [10]. Based on the variable structure systems (VSS) theory and, in particular, on the second-order sliding-mode (2-SM) methodology, a tracking controller is designed for the AUV which includes the unmodelled actuator dynamics and the presence of external uncertain disturbances [11].

In practice, an AUV must often operate in the presence of ocean currents. Motivated by the considerations, this paper presents a solution to the trajectory tracking problem of the underactuated AUV in the presence of ocean currents. We divide the tracking error system into two simple subsystems which we can stabilize independently of each other. The control algorithm proposed builds on Lyapunov stability theory and backstepping design techniques.

The organization of the paper is as follows. Section 2 presents the AUV model and problem formulation. Section 3 is devoted to the control design. Some simulations are given in Section 4 to demonstrate the effectiveness of the proposed controller. Section 5 concludes the paper.

2. AUV Model and Problem Formulation

This section describes the kinematic and dynamic equations of motion of the AUV of Figure 2 on the horizontal plane and formulates the problem of controlling it to track a desired trajectory in the presence of ocean currents. Following standard practice, the general kinematic and dynamic equations of motion of the AUV can be developed using a global coordinate frame $\{I\}$ and a body-fixed coordinate frame $\{B\}$ that are depicted in Figure 1.

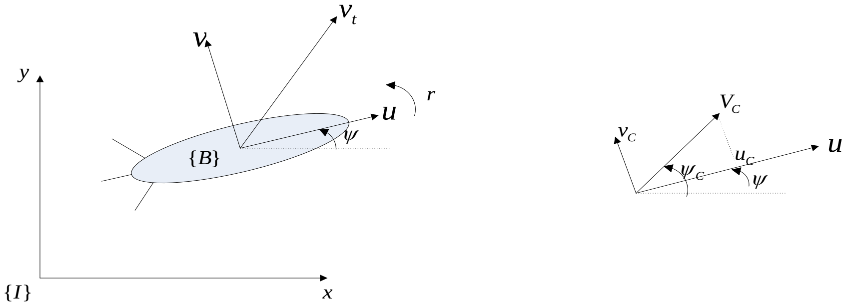

Figure 2. The Model of AUV on the Horizontal Plane in the Presence of Ocean Currents

Furthermore, we assume that the inertia, added mass and damping matrices are diagonal. In the presence of ocean currents, the model of the AUV on the horizontal plane can be described by

$$\begin{cases} \dot{x} = u_r \cos\psi - v_r \sin\psi + V_C \cos\psi_C \\ \dot{y} = u_r \sin\psi + v_r \cos\psi + V_C \sin\psi_C \\ \dot{\psi} = r \\ \dot{u}_r = \dfrac{m_{22}}{m_{11}} v_r r - \dfrac{d_{11}}{m_{11}} u_r + \dfrac{1}{m_{11}} F_u \\ \dot{v}_r = -\dfrac{m_{11}}{m_{22}} u_r r - \dfrac{d_{22}}{m_{22}} v_r \\ \dot{r} = \dfrac{m_{11} - m_{22}}{m_{33}} u_r v_r - \dfrac{d_{33}}{m_{33}} r + \dfrac{1}{m_{33}} F_r \end{cases} \tag{1}$$

where (x, y) denotes the coordinates of the AUV in the earth-fixed frame, ψ is the heading angle of the AUV, and u, v and r denote the velocity in surge, sway and yaw respectively, the surge force F_u and the yaw torque F_r are consider as the control inputs. In the presence of a constant and un-rotational ocean currents, $(u_c, v_c) \neq 0$, u and v are given by $u = u_r + u_c$ and $v = v_r + v_c$, where (u_r, v_r) is the relative body-current linear velocity vector. The positive constant terms $m_{ii}, 1 \leq i \leq 3$ denote the AUV inertia including added mass. The positive constant terms $d_{jj}, 1 \leq j \leq 3$ represent the hydrodynamic damping in surge, sway and yaw [12]. For simplicity, we ignore the higher nonlinear damping terms. Since the only two propellers are the force in surge and the control torque in yaw, AUV model (1) is underactuated. In the equations, and for clarity of presentation, it is assumed that the AUV is neutrally buoyant and that the centre of buoyancy coincides with the centre of gravity.

For system (1), we assume that a feasible reference trajectory $(x_d, y_d, \psi_d, u_d, v_d, r_d, X_d, N_d)$ is given, a trajectory satisfying

$$\begin{cases} \dot{x}_d = u_d \cos\psi_d - v_d \sin\psi_d \\ \dot{y}_d = u_d \sin\psi_d + v_d \cos\psi_d \\ \dot{\psi}_d = r_d \\ \dot{u}_d = \dfrac{m_{22}}{m_{11}} v_d r_d - \dfrac{d_{11}}{m_{11}} u_d + \dfrac{1}{m_{11}} F_{ud} \\ \dot{v}_d = -\dfrac{m_{11}}{m_{22}} u_d r_d - \dfrac{d_{22}}{m_{22}} v_d \\ \dot{r}_d = \dfrac{m_{11} - m_{22}}{m_{33}} u_d v_d - \dfrac{d_{33}}{m_{33}} r_d + \dfrac{1}{m_{33}} F_{rd} \end{cases}$$

Where (x_d, y_d, ψ_d) denotes the desired position and orientation of the virtual AUV. (u_d, v_d, r_d) denotes the desired velocities. (F_{ud}, F_{rd}) is the reference inputs in surge and yaw.

Define the tracking errors

$$\begin{cases} x_e = \cos\psi(x - x_d) + \sin\psi(y - y_d) \\ y_e = -\sin\psi(x - x_d) + \cos\psi(y - y_d) \\ \psi_e = \psi - \psi_d \\ u_e = u - u_d \\ v_e = v - v_d \\ r_e = r - r_d \end{cases}$$

In this way, the closed-loop tracking error system can be expressed as shown in the following equation

$$\begin{cases} \dot{x}_e = r_e y_e + r_d y_e + u_e + (1-\cos\psi_e)u_d - \sin\psi_e v_d + V_C \cos\psi_C \\ \dot{y}_e = -r_e x_e - r_d x_e + v_e + \sin\psi_e u_d + (1-\cos\psi_e)v_d + V_C \sin\psi_C \\ \dot{\psi}_e = r_e \\ \dot{u}_e = \dfrac{m_{22}}{m_{11}}(vr - v_d r_d) - \dfrac{d_{11}}{m_{11}} u_e + \dfrac{1}{m_{11}}(F_u - F_{ud}) \\ \dot{v}_e = -\dfrac{m_{11}}{m_{22}} u_e r_d - \dfrac{d_{22}}{m_{22}} v_e \\ \dot{r}_e = \dfrac{m_{11} - m_{22}}{m_{33}}(uv - u_d v_d) - \dfrac{d_{33}}{m_{33}} r_e + \dfrac{1}{m_{33}}(F_r - F_{rd}) \end{cases} \tag{2}$$

The tracking control problem of the AUV is transformed to a stabilization one of (2). Then, the problem considered in this paper can be formulated as follows:

Consider the underactuated AUV with the kinematic and dynamic equation given by (1). Derive a feedback control law for F_u and F_r such that closed-loop system (2) is input-to-state stable in the presence of known ocean currents.

3 Controller Design

As mentioned above, the control objective now is to stabilize error system (2). Our main goal is to subdivide the tracking control problem into two simpler and 'independent' problems: position and orientation tracking, then we design the controllers for the two subsystems independently. Specially, the velocity of ocean current is considered with bounded input for the position tracking system. For simplicity, the reference velocity r_d is considered with constant value.

Theroem 1. Consider underactuated AUV system (2) with the control law

$$F_u = F_{ud} + m_{22} v_e - m_{11} z_{x_e} - m_{22}(vr - v_d r_d) + d_{11} u_e - k_2 m_{11} \dot{z}_{x_e} - k_3 m_{11} z_{u_e} \tag{3}$$

$$F_r = F_{rd} - (m_{11} - m_{22})(uv - u_d r_d) + d_{33} r_e - m_{33}\psi_e - k_4 m_{33} r_e \tag{4}$$

where k_i $(i = 1, 2, 3, 4)$ satisfies

$$2k_1^3 m_{22}^2 d_{22} - 4k_1 m_{22} d_{22}(m_{11} - m_{22} r_d) + m_{11}^2 (m_{11} - m_{22} r_d) < 0$$

$$k_2 = \frac{m_{11}}{m_{22}} k_1$$

$$k_3, k_4 > 0$$

If F_{ud}, F_{rd} are bounded and reference velocity r_d satisfies

$$0 < r_d < \frac{m_{11}}{m_{22}}$$

and the velocity of ocean currents V_C is bounded, then trajectory tracking error system (2) is input-to-state stable.

Proof. The specific implementation process is divided into three steps:

Step 1: error system (2) can be written into the subsystem

$$\Sigma_1\text{:} \begin{cases} \dot{x}_e = r_d y_e + u_e + V_C \cos\psi_C + (1-\cos\psi_e)u_d - \sin\psi_e v_d + r_e y_e \\ \dot{y}_e = -r_d x_e + v_e + V_C \sin\psi_C + \sin\psi_e u_d + (1-\cos\psi_e)v_d - r_e x_e \\ \dot{u}_e = \dfrac{m_{22}}{m_{11}}(vr - v_d r_d) - \dfrac{d_{11}}{m_{11}} u_e + \dfrac{1}{m_{11}}(F_u - F_{ud}) \\ \dot{v}_e = -\dfrac{m_{11}}{m_{22}} u_e r_d - \dfrac{d_{22}}{m_{22}} v_e \end{cases} \tag{5}$$

and the subsystem

$$\Sigma_2\text{:} \begin{cases} \dot{\psi}_e = r_e \\ \dot{r}_e = \dfrac{m_{11} - m_{22}}{m_{33}}(uv - u_d v_d) - \dfrac{d_{33}}{m_{33}} r_e + \dfrac{1}{m_{33}}(F_r - F_{rd}) \end{cases} \tag{6}$$

Based on Lyapunov theory, the stability of Σ_1 is identified with the following system

$$\Sigma_3\text{:} \begin{cases} \dot{x}_e = r_d y_e + u_e + V_C \cos\psi_C \\ \dot{y}_e = -r_d x_e + v_e + V_C \sin\psi_C \\ \dot{u}_e = \dfrac{m_{22}}{m_{11}}(vr - v_d r_d) - \dfrac{d_{11}}{m_{11}} u_e + \dfrac{1}{m_{11}}(F_u - F_{ud}) \\ \dot{v}_e = -\dfrac{m_{11}}{m_{22}} u_e r_d - \dfrac{d_{22}}{m_{22}} v_e \end{cases} \tag{7}$$

Then, the next aim is to design control input F_u and F_r that stabilize the system Σ_2 and Σ_3.

Step 2: Let

$$\alpha_{x_e} = k_1 y_e + \frac{V_C \sin\psi_C}{r_d}$$

where k_1 is a positive constant.

Introduce error variable

$$z_{x_e} = x_e - \alpha_{x_e} = x_e - k_1 y_e - \frac{V_C \sin\psi_C}{r_d}$$

Choosing the candidate Lyapunov function

$$V_1 = \frac{1}{2} y_e^2 + \frac{1}{2} z_{x_e}^2 + \frac{m_{22}^2}{2m_{11}^2 r_d} v_e^2$$

and computing its derivative, one gives

$$\begin{aligned}
\dot{V}_1 &= y_e \dot{y}_e + z_{x_e} \dot{z}_{x_e} + \frac{m_{22}^2}{m_{11}^2 r_d} v_e \dot{v}_e \\
&= y_e(-r_d x_e + v_e + V_C \sin\psi_C) + z_{x_e}(r_d y_e + u_e + V_C \cos\psi_C + k_1 r_d x_e - k_1 v_e - k_1 V_C \sin\psi_C) \\
&\quad + \frac{m_{22}^2}{m_{11}^2 r_d} v_e \left(-\frac{m_{11}}{m_{22}} u_e r_d - \frac{d_{22}}{m_{22}} v_e\right) \\
&= -k_1 r_d y_e^2 + y_e v_e + k_1 r_d z_{x_e}^2 + z_{x_e}(k_1^2 r_d y_e + u_e - k_1 v_e + V_C \cos\psi_C) - \frac{m_{22}}{m_{11}} u_e v_e - \frac{m_{22} d_{22}}{m_{11}^2 r_d} v_e^2
\end{aligned}$$

Let

$$\alpha_{u_e} = -k_2 z_{x_e}$$

where k_2 is a positive constant. Introduce error variable $z_{u_e} = u_e - \alpha_{u_e}$, considering candidate Lyapunov function $V_2 = V_1 + \frac{1}{2} z_{u_e}^2$, its time derivative becomes

$$\begin{aligned}
\dot{V}_2 &= \dot{V}_1 + z_{u_e} \dot{z}_{u_e} \\
&= -k_1 r_d y_e^2 + y_e v_e - (k_2 - k_1 r_d) z_{x_e}^2 - \frac{m_{22} d_{22}}{m_{11}^2 r_d} v_e^2 + z_{x_e} V_C \cos\psi_C + \left(\frac{k_2 m_{22}}{m_{11}} - k_1\right) v_e z_{x_e} \\
&\quad + k_1^2 r_d y_e z_{x_e} + z_{u_e}\left[z_{x_e} - \frac{m_{22}}{m_{11}} v_e + \frac{m_{22}}{m_{11}}(vr - v_d r_d) - \frac{d_{11}}{m_{11}} u_e + \frac{1}{m_{11}}(F_u - F_{ud}) + k_2 \dot{z}_{x_e} \right]
\end{aligned} \tag{8}$$

Let (3) holds, (8) becomes

$$\dot{V}_2 = -k_1 r_d y_e^2 + y_e v_e - (k_2 - k_1 r_d) z_{x_e}^2 - \frac{m_{22} d_{22}}{m_{11}^2 r_d} v_e^2 + \\ z_{x_e} V_C \cos\psi_C + (\frac{k_2 m_{22}}{m_{11}} - k_1) v_e z_{x_e} + k_1^2 r_d y_e z_{x_e} - k_3 z_{u_e}^2 \quad (9)$$

For simplicity, we choose the parameters as

$$\frac{k_2 m_{22}}{m_{11}} - k_1 = 0 \text{ and } k_2 - k_1 r_d > 0 \quad (10)$$

Then (9) becomes

$$\dot{V}_2 = -k_1 r_d y_e^2 + y_e v_e - (k_2 - k_1 r_d) z_{x_e}^2 - \frac{m_{22} d_{22}}{m_{11}^2 r_d} v_e^2 + z_{x_e} V_C \cos\psi_C + k_1^2 r_d y_e z_{x_e} - k_3 z_{u_e}^2$$
$$= -\left(\frac{1}{m_{11}} \sqrt{\frac{m_{22} d_{22}}{r_d}} v_e - \frac{m_{11}}{2} \sqrt{\frac{r_d}{m_{22} d_{22}}} y_e \right)^2 - \left(\sqrt{\frac{k_2 - k_1 r_d}{2}} z_{x_e} - \frac{k_1^2 r_d}{\sqrt{2(k_2 - k_1 r_d)}} y_e \right)^2$$
$$- k_3 z_{u_e}^2 + \left(\frac{m_{11}^2 r_d}{4 m_{22} d_{22}} + \frac{k_1^4 r_d}{2(k_2 - k_1 r_d)} - k_1 r_d \right) y_e^2 - \frac{k_2 - k_1 r_d}{2} z_{x_e}^2 + z_{x_e} V_C \cos\psi_C$$

Obviously

$$-\frac{k_2 - k_1 r_d}{2} z_{x_e}^2 + z_{x_e} V_C \cos\psi_C = -\frac{k_2 - k_1 r_d}{2} (1-\theta) z_{x_e}^2 - \frac{k_2 - k_1 r_d}{2} \theta z_{x_e}^2 + z_{x_e} V_C \cos\psi_C$$

where $0 < \theta < 1$. If $\|z_{x_e}\| \geq 2V_C / (k_2 - k_1 r_d)\theta$, then

$$-\frac{k_2 - k_1 r_d}{2} z_{x_e}^2 + z_{x_e} V_C \cos\psi_C \leq 0 \quad (11)$$

So far, in order to ensure $\dot{V}_2 \leq 0$, the following inequality hold

$$\frac{m_{11}^2 r_d}{4 m_{22} d_{22}} + \frac{k_1^4 r_d}{2(k_2 - k_1 r_d)} - k_1 r_d < 0$$

Then, taking into account equation (10), we have

$$2k_1^3 m_{22}^2 d_{22} - 4k_1 m_{22} d_{22} (m_{11} - m_{22} r_d) + m_{11}^2 (m_{11} - m_{22} r_d) < 0 \quad (12)$$

At this result, if $\|z_{x_e}\| \geq 2V_C / (k_2 - k_1 r_d)\theta$, $\dot{V}_2 \leq 0$, the system Σ_3 is input-to-state stable.

Step 3: Considering the subsystem Σ_2 and choosing Lyapunov function $V_3 = \frac{1}{2}r_e^2 + \frac{1}{2}\psi_{3e}^2$, the time derivative of V_3 becomes

$$\begin{aligned}\dot{V}_3 &= r_e\dot{r}_e + \psi_e\dot{\psi}_e \\ &= r_e\left[\frac{m_{11}-m_{22}}{m_{33}}\left(uv-u_d r_d\right) - \frac{d_{33}}{m_{33}}r_e + \frac{1}{m_{33}}(F_r - F_{rd}) + \psi_e\right]\end{aligned} \tag{13}$$

Let (4) holds, then the previous derivative becomes $\dot{V}_3 = -k_4 r_e^2 \le 0$ which means the subsystem Σ_2 is globally asymptotically stable.

For the overall system, we select the Lyapunov function $V = V_2 + V_3$, when controller gains satisfy

$$2k_1^3 m_{22}^2 d_{22} - 4k_1 m_{22} d_{22}(m_{11} - m_{22}r_d) + m_{11}^2(m_{11} - m_{22}r_d) < 0,$$

$$k_2 = \frac{m_{11}}{m_{22}}k_1$$

$$k_3, k_4 > 0$$

It is clear that the derivative of V satisfies

$$\begin{aligned}\dot{V} \le &-\left(\frac{1}{m_{11}}\sqrt{\frac{m_{22}d_{22}}{r_d}}v_e - \frac{m_{11}}{2}\sqrt{\frac{r_d}{m_{22}d_{22}}}y_e\right)^2 - \left(\sqrt{\frac{k_2-k_1r_d}{2}}z_{x_e} - \frac{k_1^2 r_d}{\sqrt{2(k_2-k_1r_d)}}y_e\right)^2 - k_3 z_{u_e}^2 \\ &+\left(\frac{m_{11}^2 r_d}{4m_{22}d_{22}} + \frac{k_1^4 r_d}{2(k_2-k_1r_d)} - k_1 r_d\right)y_e^2 - k_4 r_e^2 \le 0\end{aligned}$$

where $\left\|z_{x_e}\right\| \ge 2V_C/(k_2 - k_1 r_d)\theta$. So system (2) is input-to-state stable.

4. Simulation Results

In order to illustrate the performance of the proposed control scheme in the presence of a constant ocean current disturbance, simulations are carried out with a model of an AUV.

The AUV parameters are:

$$m_{11} = 50\,\text{kg},\ \ m_{22} = 31.43\,\text{kg},\ \ m_{33} = 30\,\text{kg m}^2,$$
$$d_{11} = 30\,\text{kg/s},\ \ d_{22} = 262\,\text{kg/s},\ \ d_{33} = 80\,\text{kg m}^2\text{/s}.$$

The initial conditions for reference AUV are chosen as:

$$x_d(0) = 3\,\text{m},\ \ y_d(0) = 5\,\text{m},\ \ \psi_d(0) = \pi/6\,\text{rad},$$

$$u_d(0) = 5\,\text{m/s},\ \ v_d(0) = 0\,\text{m/s},\ \ r_d(0) = 0.4\,\text{rad/s}$$

and the requirement

$$r_d(t) = 0.4 \text{ rad/s}, \quad u_d(t) = 5 \text{ m/s}.$$

The initial states for the controlled AUV are chosen as:

$$x(0) = 1 \text{ m}, \quad y(0) = 2 \text{ m}, \quad \psi(0) = 0 \text{ rad},$$

$$u_r(0) = 1 \text{ m/s}, \quad v_r(0) = 0 \text{ m/s}, \quad r(0) = 1 \text{ rad/s}.$$

The velocity of ocean currents is $V_C = 0.01$ m/s, orientation $\psi_C = \pi/3$ rad. The following results are obtained with controller gains chosen as

$k_1 = 1$, $k_2 = k_1 m_{11}/m_{22}$, $k_3 = 3$, $k_4 = 2$.

In Figure 3, the reference and the resulting trajectory of the AUV in the inertial X-Y plane are displayed. From Figure 4 it can be seen that the errors of positions and orientation converge to a very small neighborhood of zero, the AUV is not out of control. The errors in velocities are depicted in Figure 5. After a short period of time, the errors of velocities converge smoothly to zero. Figure 6 shows the control force F_u and the control torque F_r needed for tracking.

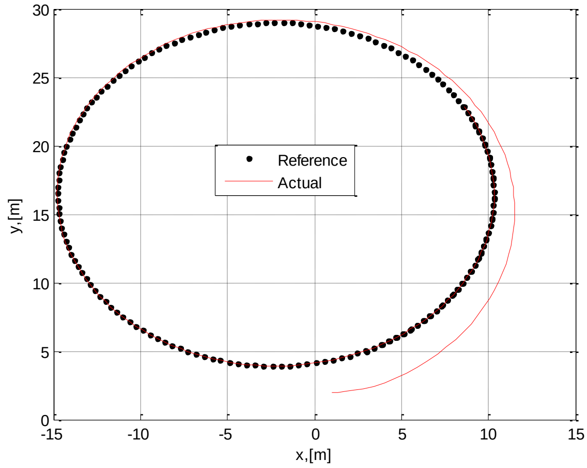

Figure 3. AUV Reference and Actual Trajectory

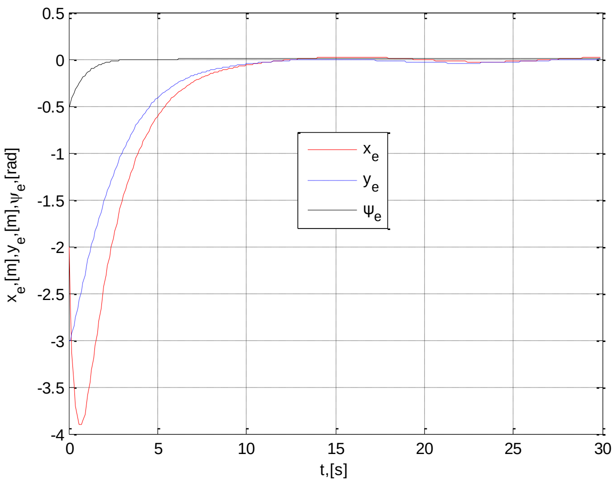

Figure 4. Positions and Orientation Errors

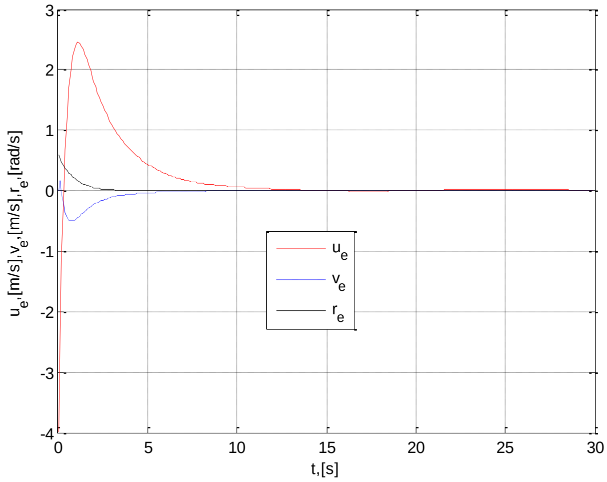

Figure 5. Velocity Tracking Errors

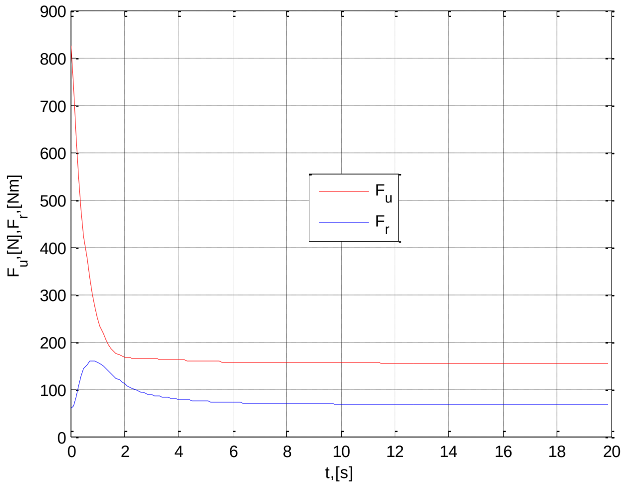

Figure 6. Control Surge Force and Yaw Torque

5 Conclusions

In this paper, the trajectory tracking control problem for an underactuated AUV has been addressed in the presence of a constant ocean current disturbance. The resulting control laws have guaranteed input-to-state stability of the tracking error dynamics. The proposed approach has reduced the problem of stabilizing the nonlinear tracking error system to two separate problems of stabilizing simpler systems. The conditions of control gains that ensure the AUV track a reference AUV have been given. Simulations have demonstrated the validity of the designed trajectory tracking control scheme.

Acknowledgments

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