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Point Stabilization of Full-actuated Autonomous Underwater Vehicle in Polar Coordinates

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Abstract

It is addressed that the point stabilization of the full-actuated autonomous underwater vehicle (AUV). The system model is established in polar coordinates and the designing methods of kinematic controller are obtained. The polar coordinates are applied to avoid Brockett's conditions. The kinematic controller is extended to dynamic controller based on Lyapunov methods and backstepping techniques. The controller is designed to ensure that the full-actuated AUV asymptotically converges to the target point. Simulations show the effectiveness of the proposed method.

Keywords*: autonomous underwater vehicle (AUV); point stabilization; polar coordinates; Lyapunov function; backstepping*

1. Introduction

The problem of point stabilization continues to pose considerable challenges to scholars since it was proposed by Samson in 1995. Point stabilization refers to the problem of steering a vehicle to a final target point with a desired orientation. Point stabilization is a challenge when the vehicle has nonholonomic constraints, since there is no smooth (or even continuous) state-feedback law [1]. Many approaches have been proposed to overcome this difficulty. For typical nonholonomic system, the point stabilization of robot has been solved better. In [2], with a polar coordinate system state equation, global stability properties can be guaranteed by smooth feedback control law. Neural networks were applied to the design of point stabilization of robot in [3]. In [4], the point stabilization of mobile robots was solved via state-space exact feedback linearization. In [5], the point stabilization for the extended chained form (ECF) was addressed. Point stabilization of wheeled mobile robots based on artificial potential field and genetic algorithm was proposed [6]. In [7], based on the human simulated intelligence control with Sensory-Motor Intelligence Scheme, a multi section proportion controller for the point stabilization of robot was addressed. In [8], the point stabilization was studied based on the transverse function approach.

Over the past few years, rapid progress in autonomous underwater vehicle (AUV) is steadily affording scientist advanced tools for ocean exploration and exploitation. AUV is employed in risky missions such as oceanographic observations, military applications, recovery of lost man-made objects, *etc* [9]. However, AUVs' models are highly nonlinear, making control problem a hard task. The point stabilization of AUV has been few studied. The design of a continuous, periodic feedback control law that asymptotically stabilizes an underactuated AUV and yields exponential convergence to the origin was proposed in [10]. In [11], the problem of dynamic positioning and way-point tracking of underactuated AUV were addressed.

In practice, much work remains to be done in some fixed point such as the fixed-point servicing in underwater cable. This work must realize accurate positioning for full-actuated AUV. Motivated by the above considerations, this paper addresses the problem

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of point stabilization of full-actuated AUV in the horizontal plane. First, the AUV model is established in polar coordinates and the designing methods of kinematic controller are obtained. Next, the kinematic controller is extended to dynamic controller through Lyapunov methods and backstepping techniques together with the characteristics of systems. The smooth control laws are designed which guarantee the AUV asymptotically converge to the target point. Simulation results are presented.

The organization of the paper is as follows. The AUV model and problem formulation is presented in Section 2. 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. Problem Formulation

2.1 AUV Model

Following standard practice, the kinematic and dynamic equations of motion of the AUV in the horizontal plane can be developed using a global coordinate frame $\{I\}$ and a body-fixed coordinate frame $\{B\}$, as depicted in Figure 1.

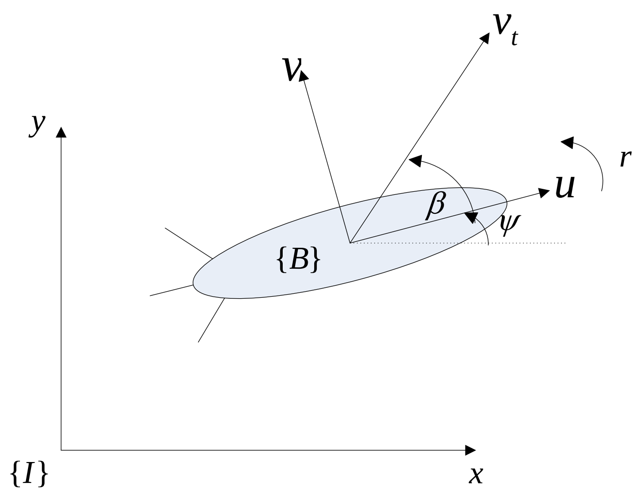

Figure 1. The Model of AUV in the Horizontal Plane

The kinematic equations take the form[12] :

$$\begin{cases} \dot{x} = u\cos\psi - v\sin\psi \\ \dot{y} = u\sin\psi + v\cos\psi \\ \dot{\psi} = r \end{cases} \tag{1}$$

where (x, y) denotes the position of the AUV in the coordinate frame $\{I\}$, ψ defines its orientation (heading angle). u is surge velocity, v is sway velocity and r is angular velocity. In Figure 1, β is the side-slip angle, v_t is the resultant velocity in u and v. We define β and v_t as:

$$\begin{cases} \beta = \arctan\dfrac{v}{u} \\ v_t = \sqrt{u^2 + v^2} \end{cases}$$

Neglecting the equations in sway, roll and yaw, the simplified dynamic equations for the full-actuated AUV in the horizontal plane can be written as [13]:

$$\begin{cases} \tau_u = m_u \dot{u} - m_v v r + d_u u \\ \tau_v = m_v \dot{v} + m_u u r + d_v v \\ \tau_r = m_r \dot{r} - m_{uv} u v + d_r r \end{cases} \tag{2}$$

where $m_u = m - X_{\dot{u}}$, $m_v = m - Y_{\dot{v}}$, $m_r = I_z - N_{\dot{r}}$ and $m_{uv} = m_u - m_v$ are mass and hydrodynamic added mass terms, $d_u = -X_u - X_{|u|u}|u|$, $d_v = -Y_v - Y_{|v|v}|v|$ and $d_r = -N_r - N_{|r|r}|r|$ capture hydrodynamic damping effects. $(\tau_u, \tau_v, \tau_r)^T$ defines the dynamic system inputs. In the equations, it is assumed that the AUV is neutrally buoyant and that the center of buoyancy coincides with the center of gravity.

2.2. Coordinate Transformation and Problem Formulation

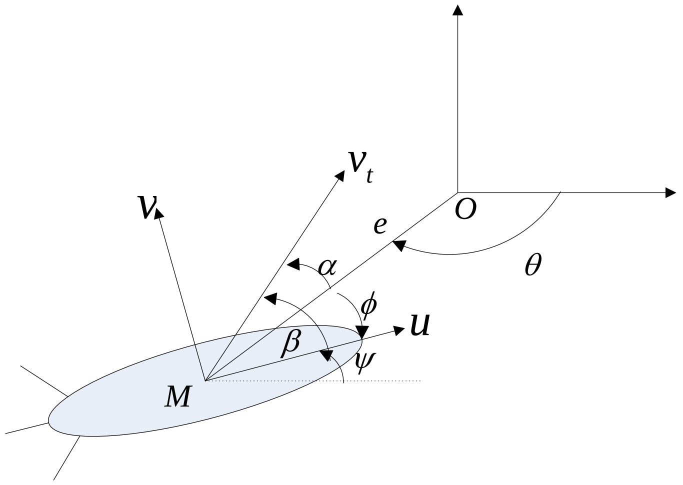

Figure 2. Coordinate Transformation

The polar coordinates are built as shown in Figure 2. The symbol e denotes the distance between the center of mass M and the pole O, and $e > 0$. Denote by ϕ the angle measured from u to e.

From Figure 2, we can conclude the relations

$$\begin{cases} x = -e\cos\theta \\ y = -e\sin\theta \end{cases} \tag{3}$$

Consider the coordinate transformation (in Figure 2), the following relations are obtained:

$$\begin{cases} e = \sqrt{x^2 + y^2} \\ \theta = \beta - \alpha + \psi + \pi \\ \phi = \alpha - \beta \end{cases} \tag{4}$$

The kinematic equations of the AUV can be rewritten in the polar coordinates to yield

$$\begin{cases} \dot{e} = -u\cos\phi + v\sin\phi \\ \dot{\phi} = \dfrac{u\sin\phi + v\cos\phi}{e} + r \\ \dot{\psi} = r \end{cases} \tag{5}$$

Note that the coordinate transformation (5) is only valid for non zero values of e, since for $e=0$ the angle ϕ is undefined. The above coordinate transformation is applied to overcome the stringent condition imposed by Brockett's result.

As mentioned above, the point stabilization problem of the full-actuated AUV can be formulated as follows:

Consider the AUV model given by (5). Given arbitrary initial positions, derive control laws for the force τ_u, the torque τ_v, τ_r so that the AUV asymptotically converges to the target point, i.e., the following should satisfy

$$\lim_{t\to\infty}(e,\phi)^T=(0,0)^T,\ \lim_{t\to\infty}(u,v,r)^T=(0,0,0)^T \text{ and } \lim_{t\to\infty}(\tau_u,\tau_v,\tau_r)^T=(0,0,0)^T$$

3. Controller Design

In this section, the simple candidate Lyapunov function is applied to derive simple and smooth control laws.

3.1. Kinematic Controller

During the kinematic controller design, the control objective is to design control input u,v and r so that $(e,\phi)^T \to (0,0)^T$ when $t\to\infty$.

Choose control input as following

$$\begin{cases} u = k_1 e\cos\phi \\ v = -k_1 e\sin\phi \end{cases} \tag{6}$$

where $k_1>0$.

Replace (6) in (5), then

$$\begin{cases} \dot{e} = -k_1 e \\ \dot{\phi} = r \\ \dot{\psi} = r \end{cases} \tag{7}$$

From $\dot{e}=-k_1e$, it can conclude that $e\to 0$ when $t\to\infty$. For $\dot{\phi}=r$, we can consider the candidate Lyapunov function $V_1=\phi^2/2$, then $\dot{V}_1=\phi\dot{\phi}=\phi r$, thus select

$$r=-k_2\phi \tag{8}$$

where $k_2>0$. The time derivative of V_1 becomes $\dot{V}_1=-k_2\phi^2\le 0$, so $\lim_{t\to\infty}\phi=0$. From (6) and (8), it can be shown that $\lim_{t\to\infty}(u,v,r)^T=(0,0,0)^T$.

The above results play an important role in the proof of the following theorem.

Theorem 1 Consider the model of the AUV described in (5) and the given initial position, together with the control law (6) and (8), then the AUV asymptotically converges to the target point.

3.2. Dynamic Controller

The above control law (6) and (8) are derived in the kinematic model of the AUV. In this section, the control laws can be extended to the dynamic model using the backstepping techniques.

Theorem 2 Consider the full-actuated AUV described in (5) and (2), together with the control law

$$\begin{cases}\tau_u = m_u\dot{\alpha}_u - k_3 z_u - m_v vr + d_u u \\ \tau_v = m_v\dot{\alpha}_v - k_4 z_v + m_u ur + d_v v \\ \tau_r = m_r\dot{\alpha}_r - k_5 z_r - \phi - m_{uv} uv + d_r r\end{cases} \quad (9)$$

where

$$\begin{cases}\dot{\alpha}_u = -k_1 u - k_1 er\sin\phi \\ \dot{\alpha}_v = -k_1 v - k_1 er\cos\phi \\ \dot{\alpha}_r = -k_2\left(\dfrac{u\sin\phi + v\cos\phi}{e} + r\right)\end{cases}$$

then the AUV asymptotically converges to the target point, i.e.,

$$\lim_{t\to\infty}\left(e,\phi,z_u,z_v,z_r\right)^T = \left(0,0,0,0,0\right)^T$$

Proof Introducing error variable

$$z = \begin{pmatrix} z_u \\ z_v \\ z_r \end{pmatrix} = \begin{pmatrix} u-\alpha_u \\ v-\alpha_v \\ r-\alpha_r \end{pmatrix}$$

where

$$\begin{cases}\alpha_u = k_1 e\cos\phi \\ \alpha_v = -k_1 e\sin\phi \\ \alpha_r = -k_2\phi\end{cases}$$

Augment now the candidate Lyapunov function with the term $z^{\mathrm{T}}Mz$ to obtain

$$V_2 = V_1 + \frac{1}{2}z^T Mz$$

where $M = diag\{m_u, m_v, m_r\}$.

The time derivative of V_2 is given by

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + m_u z_u\dot{z}_u + m_v z_v\dot{z}_v + m_r z_r\dot{z}_r \\ &= -k_2\phi^2 + m_u z_u\dot{z}_u + m_v z_v\dot{z}_v + z_r(m_r\dot{z}_r + \phi)\end{aligned}$$

Choosing

$$\begin{cases}m_u\dot{z}_u = -k_3 z_u \\ m_v\dot{z}_v = -k_4 z_v \\ m_r\dot{z}_r = -\phi - k_5 z_r\end{cases} \quad (10)$$

where $k_3, k_4, k_5 > 0$.

Then

$$\dot{V}_2 = -k_2\phi^2 - k_3 z_u^2 - k_4 z_v^2 - k_5 z_r^2 < 0$$

so $\lim_{t\to\infty}\left(e,\phi,z_u,z_v,z_r\right)^T = \left(0,0,0,0,0\right)^T$. Substitute (10) to (2), the actual force and torque become (9).

4. Simulation Results

In this section, in order to illustrate the performance of the proposed control scheme, computer simulations were carried out. The AUV parameters are set as following:

$$m_u = 1.1274, \; m_v = 1.8902, \; m_r = 0.1278, \; m_{uv} = -0.7628,$$
$$d_u = 0.0385, \; d_v = 0.1183, \; d_r = 0.0308$$

The initial conditions for AUV in polar coordinates are chosen as:

$$e(0) = 100, \phi(0) = -\pi/4, \theta(0) = \pi/3$$

The initial values of velocities are set as:

$$u(0) = 3, v(0) = 1, r(0) = 2$$

The control parameters are selected as:

$$k_1 = 1, k_2 = 1, k_3 = 3, k_4 = 2, k_5 = 1$$

Figure 3-7 shows the results of the simulations.

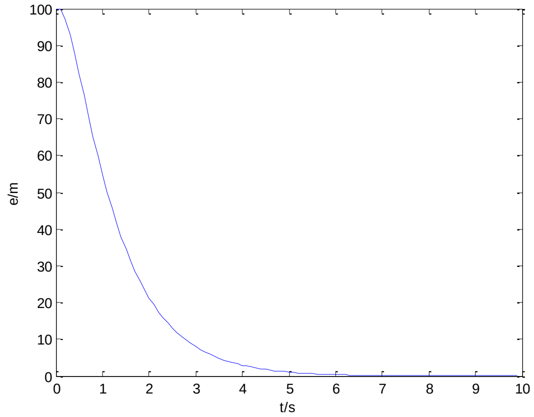

Figure 3. Time Evolution of e

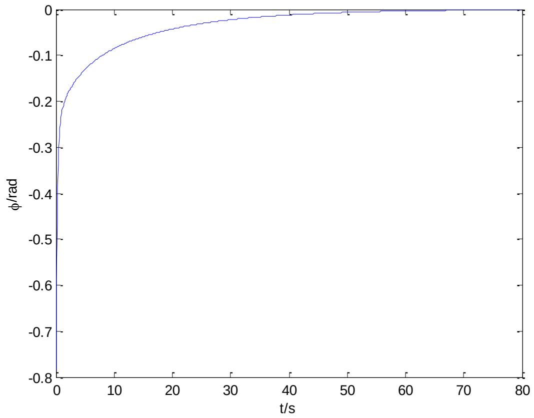

Figure 4. Time Evolution of ϕ

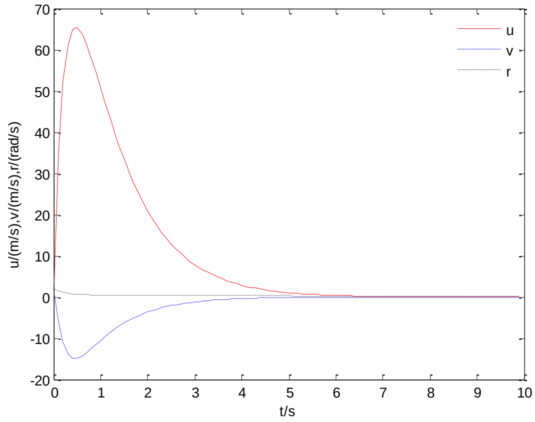

Figure 5. Time Evolution of Velocities u, v, r

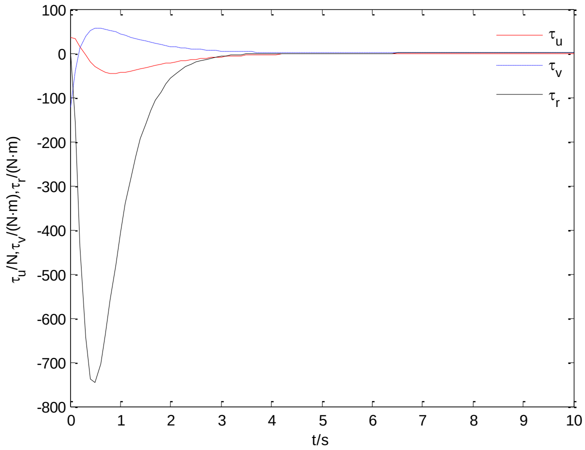

Figure 6. Time Evolution of τ_u, τ_v, τ_r

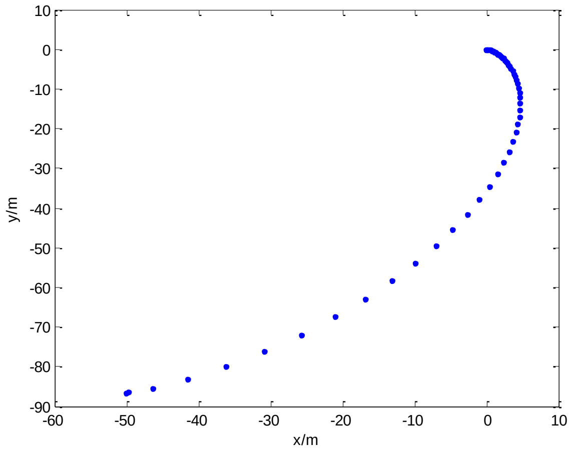

Figure 7. AUV Motion Curves

In Figure 3 and Figure 4, the variable e and the variable ϕ converge to zero. As Figure 5 shows, the velocities converge to the reference velocities. Figure 6 shows the control input τ_u, τ_v, τ_r needed for point stabilization. From Figure 7, it can see that the AUV converges to the desired point. The proposed controller for the AUV guarantees the stable response and convergence to the target point smoothly. Therefore, the simulation results demonstrate that the controller is effective to solve the point stabilization problem of full-actuated AUV.

5. Conclusions

In this paper, the point stabilization control problem for a full-actuated AUV has been addressed. The key idea is that the polar coordinates have been introduced. The coordinate transformation has been applied to overcome the stringent Brockett's condition. Controller design rely on backstepping techniques and Lyapunov theory. The resulting control laws can guarantee that the AUV asymptotically converges to the target point. Simulations have demonstrated the validity of the designed control schemes.

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