Study on Horizontal Path Tracking Control Method for the Spherical Amphibious Robot

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Abstract - In order to improve the autonomy of spherical amphibious robots in underwater environment monitoring, and break through the artificial real-time control, improve the efficiency of environmental monitoring, this paper proposed a horizontal path tracking control method for the spherical amphibious robots. Firstly, the dynamics and kinematics model of the spherical amphibious robot were analyzed, and the dynamic and kinematics model of the spherical amphibious robot was established. The six-degree-of-freedom motion of the robot was decoupled and the horizontal three-degree-of-freedom motion model was obtained. Secondly, the horizontal path tracking error model of spherical amphibious robot was established in the Seret-Frenet coordinate system, and the path tracking error equation was given. Then, according to the horizontal motion equation of spherical amphibious robot, an adaptive controller based on backstepping sliding mode was designed. Finally, the simulation experiment of the horizontal sinusoidal path tracking was carried out. The experimental results verified the feasibility and validity of the controller designed in this paper, and the results proved that the horizontal path tracking effect of spherical amphibious robot was good.

Index terms - Dynamics. Kinematics. Path tracking. Spherical amphibious robot. Controller

I. INTRODUCTION

Since the beginning of the 21st century, many marine countries have begun to develop modern marine environmental monitoring technology for precious marine resources, and with the progress of science and technology, underwater vehicles have been widely used in underwater environmental monitoring. However, in order to complete long-term, long-distance and high-precision monitoring tasks, the robots used for underwater environment monitoring need to rely on the high degree of autonomy of the robot. In order to improve the autonomous performance of underwater vehicles, path tracking technology is indispensable.

In 2016, an underwater robot named FIFIFISH, developed by Shenzhen Fin Source Company, appeared at CES Exhibition in the United States. This robot can be used for underwater environmental monitoring tasks such as marine lake rescue, deep-sea sunken ship excavation, underwater detection of wharfs, water quality detection of rivers and lakes, aquaculture environment monitoring, etc. [1]. However, because the robot is connected with the controller by cable, the scope of operation is limited and it lacks certain autonomy. In 2016, Tianjin Deep Pin Far Ocean Equipment Technology Co., Ltd. released an underwater UAV named "White Shark". It has a unique all-solid-state propulsion system and a nine-axis all-attitude balanced motion system, with underwater additional cameras, sonars, underwater positioning, manipulators, water quality sensors, 3D cameras and so on. It can be used for underwater environmental monitoring tasks such as ocean ranch observation, pipeline inspection, underwater exploration, etc. [2]. It also belongs to the cable robot, the maximum cable length can reach 400 meters, depending on the real-time operation of staff. An underwater robot named Remus-100 equipped by the professional demining squadron of the United States Navy is developed by Hydroid Company (the American branch of the Consburg Maritime Company). Its main tasks are to report underwater conditions, mine reconnaissance and underwater patrol in shallow water [3]. The U.S. Navy also combined Remus-600, an improved underwater vehicle of the Remus-100, with the formation of marine fauna to detect submerged mines within 100 meters and to track [4] and observe fish flocks[5]. Cyro, a 5-foot-long machine jellyfish developed by Virginia Tech's School of Engineering in 2013, can be used to monitor ocean currents or clean up oil spills. Machine jellyfish can also play an important role in military surveillance operations. Cyro has a basic control system. Cyro is programmed beforehand to work out the tasks and motion paths that need to be completed. After entering the water, Cyro will execute the tasks according to the pre-set procedures, which has a high degree of autonomy [6].

It is not difficult to see that the robot used for underwater environmental monitoring will use the path tracking technology in search and rescue, underwater pipeline detection, military
reconnaissance, underwater patrol and other tasks. Therefore, this paper studies the horizontal path tracking control of spherical amphibious robot. The robot model is shown in Fig. 1[7][8]. The spherical amphibious robot is equipped with temperature sensors, water quality sensors, sound sensors, high-definition cameras and other equipment, which can be used to perform a variety of underwater environmental monitoring tasks[9]. A good path tracking technology can not only improve the autonomy of the robot, but also greatly improve the scope of operation of the robot.

II. KINEMATICS AND DYNAMICS MODELING FOR THE SPHERICAL AMPHIBIOUS ROBOT

A. Set Coordinate System

In order to accurately describe the motion of spherical amphibious vehicle with six degrees of freedom, a three-dimensional space coordinate is established as shown in Fig. 1. \( \{I\} $$- \xi \eta \zeta $$ is a fixed coordinate with the earth as a reference point. \( \{o\}-xyz $$ is the motion coordinate connecting the robot itself [10]. The six-degree-of-freedom motion vector form of spherical amphibious robot is described as follows:

\[
\dot{\eta} = \begin{bmatrix} \eta_1^T, \eta_2^T \end{bmatrix}^T, \eta = \begin{bmatrix} \xi, \eta, \zeta \end{bmatrix}^T, \eta = \begin{bmatrix} \phi, \theta, \psi \end{bmatrix}^T
\]

\[
V = \begin{bmatrix} V_1^T, V_2^T \end{bmatrix}^T, V_1 = \begin{bmatrix} u, v, w \end{bmatrix}^T, V_2 = \begin{bmatrix} p, q, r \end{bmatrix}^T
\]

\( \eta_1 \) and \( \eta_2 \) are position vectors and attitude vectors, which are defined in a fixed coordinate system. \( \phi, \theta, \psi \) are roll angle, pitch angle and bow angle respectively. \( V_1 \) and \( V_2 \) are linear and angular velocities, which are defined in motion coordinates. \( u, v, w \) represent longitudinal velocity, transverse velocity and vertical velocity, respectively. \( p, q, r \) represent roll angular velocity, longitudinal angular velocity and yaw angular velocity, respectively. Therefore, the underwater position and attitude of spherical amphibious robot in a fixed coordinate system are represented by \( \eta = [\eta_1^T, \eta_2^T]^T\). Linear and angular velocities of spherical amphibious robots in motion coordinates are represented by \( V = [V_1^T, V_2^T]^T\).

B. Kinematic Model

According to the existing literature, the kinematics equation of spherical amphibious robot can be written as follows[11]:

\[
\dot{\eta} = J(\Theta)V
\]

The linear velocity conversion of spherical amphibious robot can be expressed as:

\[
\dot{\eta}_1 = J_1(\eta_2)V_1
\]

Where

\[
J_1(\eta_2) = \begin{bmatrix}
c \psi c \theta - c \psi s \phi s \theta + s \psi c \phi & -s \psi c \theta - c \psi s \phi s \theta + c \psi c \phi \\
-c \psi s \phi s \theta - c \psi c \phi & s \psi s \phi s \theta - c \psi c \phi \\
c \theta c \phi & c \theta s \phi \\
\end{bmatrix}
\]

\( J_1(\eta_2) \) is the transformation matrix of Euler angle, \( c = \cos, s = \sin \). Similarly, angular velocity conversion can be expressed as follows:

\[
\dot{\eta}_2 = J_2(\eta_2)V_2
\]

Where

\[
J_2(\eta_2) = \begin{bmatrix}
1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi / \cos \theta & \cos \phi / \cos \theta \\
\end{bmatrix}
\]

Therefore, the complete transformation from motion coordinate system to fixed coordinate system is:

\[
\begin{bmatrix}
\dot{\eta}_1 \\
\dot{\eta}_2
\end{bmatrix} = J_1(\eta_2)J_2(\eta_2)\begin{bmatrix} V_1 \\
V_2
\end{bmatrix}
\]

C. Dynamic Model

According to Newton-Euler equation, the six-degree-of-freedom dynamic equation of spherical amphibious robot can be expressed as follows in motion coordinate system:

\[
M \dot{V} + C(V)V + D(V)\dot{V} + g(\eta) = \tau
\]

Where \( M \) is the sum of inertial matrix \( M_A \) and additional mass matrix \( M_R \), \( C(V) \) is Coriolis and centrifugal matrix, \( D(V) \) is damping matrix, \( g(\eta) \) is a vector containing the restoring terms formed by the robots buoyancy and gravitational terms, \( \tau \) is a vector including control forces and moments.

In order to facilitate the design of the controller, the six-degree-of-freedom motion of spherical amphibious robot is decoupled and a three-degree-of-freedom horizontal motion model is obtained[12].

Horizontal kinematics equation can be expressed as:

\[
\begin{align*}
\dot{x} &= u \cos \psi - v \sin \psi \\
\dot{y} &= u \sin \psi + v \cos \psi \\
\dot{z} &= r
\end{align*}
\]

Horizontal dynamic equation can be expressed as:

\[
\begin{align*}
(m - X_u)\ddot{u} &= (m - Y_v) \dot{v} + \left( X_u + X_{\phi \theta} \right) u + X \\
(m - Y_v)\ddot{v} &= -(m - X_u) \dot{u} r + \left( Y_v + Y_{\phi \theta} \right) v + N \\
(I_z - N_r)\ddot{r} &= -(X_u - Y_v) \dot{u} v + \left( N_r + N_{\phi \theta} \right) r + N
\end{align*}
\]

Where \( X, N \) is a jet force and moments generated by propelling a water jet motor.
The model parameters of spherical amphibious robot are as follows [13]:

\[
M = M_R + M_A \\
M_A = \text{diag}\{X_u, Y_v, Z_w, K_p, M_q, N_r\} \\
= \text{diag}\{4.09, 4.09, 4.09, 0.0554, 0.0629\} \\
M_R = \text{diag}\{m, m, m, I_x, I_y, I_z\} \\
= \text{diag}\{3.58, 3.58, 3.58, 0.0, 0.0075\} \\
D(V) = \text{diag}\{X_u, Y_v, Z_w, K_p, M_q, N_r\} \\
= \text{diag}\{9.78, 9.78, 9.78, 1.22, 1.22, 1.22\}
\]

Because the motion of spherical amphibious robot belongs to low-speed motion, the linear damping term plays a dominant role, so the non-linear damping term can be neglected.

III. DESIGN FOR THE PATH TRACKING CONTROLLER

A. Path Tracking Error Model

Fig. 3 is a horizontal path tracking diagram of a spherical amphibious robot. \{I\}, \{F\} and \{B\} represent fixed coordinate system, Serret-Frenet coordinate and motion coordinate respectively.

“Path” is a given path on the horizontal plane, and it is a continuous smooth curve with \(\mu\) as a variable. Point P is any point on a given path curve with a certain velocity \(U_P\), and P is the origin of \{F\} coordinate. In modeling analysis, the center of mass Q of spherical amphibious robot is used to replace the whole robot. In \{F\} coordinate, Q point is represented by \(\{x_e, y_e, 0\}\). In short, the horizontal path tracking problem of spherical amphibious robots can be transformed into designing appropriate controllers to make the centroid Q of the robot approach point P in the \{F\} coordinate. The reference point \(P(\xi, \eta, 0)\) on path is uniquely determined by parameter \(\mu\). Then \(\mu\) can represent the arc length of the path of the curve to be tracked, \(c(\mu)\) represents the curvature at any point in the path. Define tracking error \(\psi_e = \psi - \psi_d\). The path tracking error of spherical amphibious robot under horizontal kinematics equation can be obtained[14].

\[
\begin{align*}
\dot{x}_e &= y_c(\mu) \mu + u \cos \psi_e - \dot{\mu} \\
\dot{y}_e &= -x_c(\mu) \mu + u \sin \psi_e \\
\dot{\psi}_e &= r + \dot{\beta} - c(\mu) \dot{\mu}
\end{align*}
\]  

(11)

Thus, we can describe the problem of path tracking as follows: the control law of longitudinal thrust X and steering moment N is designed according to the horizontal motion model of spherical amphibious robot, and the control law of path tracking is designed by referring to the horizontal path tracking error equation of spherical amphibious robot, so that the robot can track the given path from any initial position to ensure the longitudinal speed and the angle converges to the desired value[15][16].

B. Design of Heading Angle Controller

From the kinematics and dynamics equations of the horizontal plane of the spherical robot, the model of the horizontal heading angle can be obtained, Among them, \(f(\cdot)\) is the external interference factor.

\[
\begin{align*}
\dot{\psi} &= r \\
\dot{r} &= \frac{(X_u - Y_v)}{(I_z - N_r)} + \frac{(N_r + N_r f_N)}{(I_z - N_r)} r + \frac{N}{(I_z - N_r)} f_N
\end{align*}
\]  

(12)

(12)

It can be seen that the model of heading angle is a second-order nonlinear system, and the heading angle tracking error is defined as

\[
z_1 = \psi - \psi_d
\]  

(13)

So

\[
z_1 = \psi - \psi_d = r - \psi_d
\]  

(14)

A new state variable \(z_2\) is introduced here.:

\[
z_2 = r + k_1 z_1 - \psi_d
\]  

(16)

Define Lyapunov function:

\[
V_1 = \frac{1}{2} z_1^2
\]  

(17)

So

\[
\dot{V}_1 = z_1 \dot{z}_1 = z_1 (r - \psi_d)
\]  

(18)

The following sliding surface is designed:

\[
S_1 = c_1 z_1 + z_2
\]  

(19)

Define Lyapunov function:

\[
V_2 = V_1 + \frac{1}{2} S_1^2
\]  

(20)
We can get
\[ V_2 = \dot{V}_1 + S_1 \dot{S}_1 \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + S_1 \dot{S}_1 \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + S_1 (c_1 \dot{z}_1 + \dot{z}_2) \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + S_1 (c_1 \dot{z}_1 + r - \alpha) \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + S_1 (c_1 \dot{z}_1 - \frac{(x_u - y_u)}{(I_z - N_r)} r + \alpha - \dot{\psi}_d) \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + S_1 (c_1 \dot{z}_1 - \frac{(X_u - Y_u)}{(I_z - N_r)} uv + \frac{(N_r + N_{qH})}{(I_z - N_r)} r + \frac{N}{(I_z - N_r)} + \frac{f_r}{(I_z - N_r)} + \dot{\alpha} - \dot{\psi}_d) \]
(21)

Because of the existence of external disturbance \( f_r \) in the system, the method of adaptive law is chosen here to estimate the parameters of external disturbance \( f_r \). Let \( \hat{f}_r \) be the estimated value of external interference \( f_r \).
\[ \hat{f}_r = f_r - \tilde{f}_r \]
(22)

Where (22) is the estimation error of external interference \( f_r \).

Define Lyapunov function:
\[ V_3 = V_2 + \frac{1}{2\gamma_1} \tilde{f}_r^2 \]
(23)

So
\[ \dot{V}_3 = \dot{V}_2 + \frac{1}{\gamma_1} \tilde{f}_r \dot{f}_r \]
\[ = \dot{V}_2 + \frac{1}{\gamma_1} \tilde{f}_r \left( \dot{f}_r - \tilde{f}_r \right) \]
(24)

\[ = \dot{V}_2 + \frac{1}{\gamma_1} \tilde{f}_r \dot{f}_r \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + \left( c_1 \dot{z}_1 - \frac{(X_u - Y_u)}{(I_z - N_r)} uv + \frac{(N_r + N_{qH})}{(I_z - N_r)} r + \frac{N}{(I_z - N_r)} + \frac{f_r}{(I_z - N_r)} + \dot{\alpha} - \dot{\psi}_d \right) \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + \left( c_1 \dot{z}_1 - \frac{(X_u - Y_u)}{(I_z - N_r)} uv + \frac{(N_r + N_{qH})}{(I_z - N_r)} r \right) \]
\[ + S_1 \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + \left( c_1 \dot{z}_1 - \frac{(X_u - Y_u)}{(I_z - N_r)} uv + \frac{(N_r + N_{qH})}{(I_z - N_r)} r \right) + S_1 \]
\[ = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 + \left( c_1 \dot{z}_1 - \frac{(X_u - Y_u)}{(I_z - N_r)} uv + \frac{(N_r + N_{qH})}{(I_z - N_r)} r \right) + \frac{1}{\gamma_1} \tilde{f}_r \left( \dot{f}_r - \gamma_1 S_1 \right) \]
(25)

The course angle controller is designed as follows:
\[ N = \left( I_z - N_r \right) \frac{(X_u - Y_u) uv - (N_r + N_{qH}) r}{(I_z - N_r)} - c_1 \dot{z}_1 \]
\[ + \alpha + \psi_d - \frac{\dot{f}_r}{(I_z - N_r)} - h_l (S_1 + \epsilon_1 \text{sgn}(S_1)) \]
\[ \dot{\alpha} + \dot{\psi}_d - \frac{\dot{f}_r}{(I_z - N_r)} - h_l (S_1 + \epsilon_1 \text{sgn}(S_1)) \]
(25)

The adaptive law as follows:
\[ \dot{f}_r = \gamma_2 S_2 \]
(26)

It can be obtained from the heading angle controller and the adaptive law:
\[ \dot{V}_3 = -k_1 \dot{z}_1^2 + z_1 \dot{z}_2 - h_l S_1^2 - h_l \epsilon_1 |S_1| \]
(27)

We can take
\[ Q_1 = \begin{bmatrix} k_1 + h_l c_1 & h_l c_1 - \frac{1}{2} \\ h_l c_1 - \frac{1}{2} & h_l \end{bmatrix} \]
(28)

Because
\[ z^T Q_1 z = [z_1 z_2] Q_1 \]
\[ = k_1 \dot{z}_1^2 - z_1 \dot{z}_2 + h_l S_1^2 \]
(29)

So we can be written as
\[ V_3 \leq -z^T Q_1 z - h_l \epsilon_1 |S_1| \]
(30)

Then
\[ |Q_1| = h_l (k_1 + h_l c_1) - \left( h_l c_1 - \frac{1}{2} \right)^2 \]
\[ = h_l (k_1 + c_1) - \frac{1}{4} \]

By choosing the appropriate value of \( h_1, c_1, k_1 \) it can make \( |Q_1| > 0 \), this ensures the first derivative of \( V_3 \) is greater than zero. It satisfies Lyapunov's criterion[17].

C. Design of Longitudinal Speed Controller

The horizontal longitudinal velocity model of spherical amphibious robot is as follows:
\[ u = \left( \frac{m - Y_r}{r} \right) v_r + \left( \frac{X_u + X_u H}{r} \right) u \]
\[ + \frac{X}{(m - X_u)} + \frac{f_r}{(m - X_u)} \]
(32)

According to the design method of course angle controller, the speed tracking controller can be obtained as follows:
\[ X = -\left( \frac{m - Y_r}{r} \right) v_r - \left( \frac{X_u + X_u H}{r} \right) u - \left( m - X_u \right) \]
\[ \dot{u} = -\left( \frac{m - Y_r}{r} \right) v_r - \left( \frac{X_u + X_u H}{r} \right) u - \left( m - X_u \right) \]
(33)

The adaptive control law is designed as follows[18]:
\[ \dot{f}_u = \gamma_2 S_2 \]
(34)

In summary, under the condition of external disturbance, the robot tracks the given path under the dual action of controller and control law, and ensures that the speed of the robot converges to the desired speed, and the tracking error \( x_e, y_e \) is globally asymptotically stable.

IV. SIMULATION AND RESULTS
In order to verify the effectiveness of the designed horizontal path tracking controller, a spherical amphibious robot has been simulated. In this paper, taking sinusoidal tracking as an example, we compare the path tracking of spherical amphibious robots with and without external disturbances, and discuss the feasibility and effectiveness of the horizontal path tracking controller based on adaptive sliding mode inversion control method. The initial state of the robot is $\xi(0)=10\text{m}, \eta(0)=0$; the initial velocity is $u(0)=v(0)=r(0)=0\text{m/s}$; the initial attitude angle is $\psi(0)=\pi/2$; the desired longitudinal velocity is $u_d=0.1\text{m/s}$.

The time-varying external disturbances are as follows:

$$f_u = 0.5\cos(t)$$
$$f_r = 0.5\sin(t)$$

(35)

The parametric equation of the straight line path is as follows:

$$\xi_p = \mu, \quad \eta_p = 2\sin\left[\frac{2\pi}{10}\right] \cdot \mu$$

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The simulation results are shown in Fig.4-8, for sinusoidal path tracking. It can be seen from the simulation curve in Fig.4 that the controller can make the spherical amphibious robot track the sinusoidal path to be tracked quickly, and the tracking effect is good. In the presence of time-varying external interference, the error between the tracking path and the desired path is small. In Fig. 5, the longitudinal velocity of the spherical amphibious robot converges rapidly to the desired velocity, and the overshoot is small; the spherical amphibious robot has no direct control force in the lateral direction, because the lateral moment will occur when the direction angle of the robot changes, which results in the change of the lateral velocity \( v \). However, it can be seen that the range of velocity change is very small and basically stabilizes near zero. At the same time, the heading angle in change of the lateral velocity \( v \). However, it can be seen that when there is external interference in the system, the system will have corresponding jitter, but the overall error is not more than 5%, which meets the actual requirements of the project.

The simulation results prove the feasibility and validity of the backstepping sliding mode adaptive controller designed in this paper. Under the action of the controller, the spherical amphibious robot can track the given path quickly and the tracking effect is good.

V. CONCLUSION AND FUTURE WORK

In this paper, the horizontal path tracking control method of spherical amphibious robot was studied. Firstly, the dynamics and kinematics of spherical amphibious robot was analyzed, and the dynamic and kinematics model of spherical amphibious robot was established. The horizontal three-degree-of-freedom motion model was obtained by decoupling the six-degree-of-freedom motion of spherical amphibious robot. A horizontal path tracking error model of spherical amphibious robots was established in the Serret-Frenet coordinate system, and the path tracking error equation was given. According to the horizontal motion equation of spherical amphibious robot, an adaptive controller based on backstepping sliding mode was designed. Finally, the simulation experiment of the horizontal sinusoidal path tracking was carried out. The experimental results verified the feasibility and validity of the controller designed in this paper, and proved that the horizontal path tracking effect of spherical amphibious robot was good. This ensured that the robot can track the given path in underwater environment monitoring. It can greatly improve the efficiency of underwater environmental monitoring.

In the future, we will extend the research on path tracking control methods of spherical amphibious robots to vertical and three-dimensional space, so that the robot can reflect its high degree of autonomy in underwater environment monitoring, and can quickly track the given path.

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