Proceedings of 2019 IEEE
International Conference on Mechatronics and Automation
August 4 - 7, Tianjin, China

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

Shuxiang Guo[1,2], Xujie Yang[1]
[1]*Tianjin Key Laboratory for Control Theory & Applications in Complicated Systems and Biomedical Robot Laboratory*
Tianjin University of Technology
Binshui Xidao 391, Tianjin, China
guo@eng.kagawa-u.ac.jp;879943940@qq.com;

Jian Guo[1*]
[2]*Intelligent Mechanical Systems Engineering Department*
Faculty of Engineering
Kagawa University
2217-20, Hayashi-cho, Takamatsu 761-0396, Japan
*Corresponding author: jianguo@tjut.edu.cn;

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

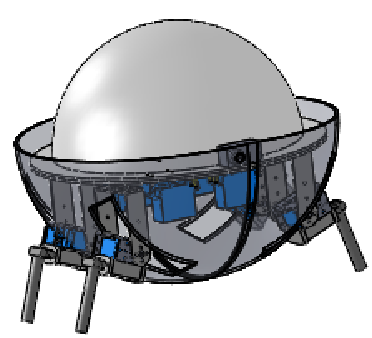

Fig.1 The model of spherical amphibious robot

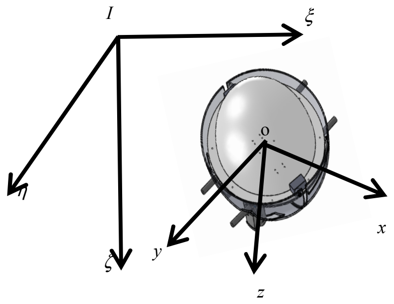

Fig.2 Coordinate frame $\{I\}-\xi\eta\zeta$ and $\{o\}-xyz$

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-}ξηζ 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:

$$\begin{gathered}\eta=\left[\eta_1^T,\eta_2^T\right]^T;\eta_1=[\xi,\eta,\zeta]^T;\eta=[\phi,\theta,\psi]^T;\\ V=\left[V_1^T,V_2^T\right]^T;V_1=[u,v,w]^T;V_2=[p,q,r]^T;\end{gathered} \tag{1}$$

η_1 and η_2 are position vectors and attitude vectors, which are defined in a fixed coordinate system.ϕ,θ,ψ 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 $\eta=[\eta^T_1,\eta_2^T]^T$,Linear and angular velocities of spherical amphibious robots in motion coordinates are represented by $V=[V^T_1,V^T_1]^T$.

B · *Kinematic Model*

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

$$\dot{\eta}=J(\Theta)V \tag{2}$$

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

$$\dot{\eta}_1=J_1(\eta_2)V_1 \tag{3}$$

Where

$$J_1(\eta_2)=\begin{bmatrix} c\psi c\theta & c\psi s\theta s\varphi-s\psi c\varphi & c\psi s\theta c\varphi+s\psi s\varphi\\ s\psi c\theta & s\psi s\theta s\varphi+c\psi c\varphi & s\psi s\theta c\varphi-c\psi s\varphi\\ -s\theta & c\theta s\varphi & c\theta c\varphi\end{bmatrix} \tag{4}$$

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

$$\dot{\eta}_2=J_2(\eta_2)V_2 \tag{5}$$

Where

$$J_2(\eta_2)=\begin{bmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta\\ 0 & \cos\varphi & -\sin\varphi\\ 0 & \sin\varphi/\cos\theta & \cos\varphi/\cos\theta\end{bmatrix} \tag{6}$$

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

$$\begin{bmatrix}\dot{\eta}_1\\ \dot{\eta}_2\end{bmatrix}=\begin{bmatrix} J_1(\eta_2) & 0_{3\times3}\\ 0_{3\times3} & J_2(\eta_2)\end{bmatrix}\begin{bmatrix} V_1\\ V_2\end{bmatrix} \tag{7}$$

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

$$M\dot{V}+C(V)V+D(V)V+g(\eta)=\tau \tag{8}$$

Where M is the sum of inertial matrix M_R and additional mass matrix M_A, C(V) is Coriolis and centripetal matrix ,D(V) is damping Matrix,$g(\eta)$ is a vector containing the restoring terms formed by the robots buoyancy and gravitational terms,τ 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：

$$\begin{cases}\dot{\xi}=u\cos\psi-v\sin\psi\\ \dot{\eta}=u\sin\psi+v\cos\psi\\ \dot{\psi}=r\end{cases} \tag{9}$$

Horizontal dynamic equation can be expressed as:

$$\begin{cases}(m-X_{\dot{u}})\dot{u}=(m-Y_{\dot{v}})vr+\left(X_u+X_{u|u|}|u|\right)u+X\\ (m-Y_{\dot{v}})\dot{v}=-(m-X_{\dot{u}})ur+\left(Y_v+Y_{v|v|}|v|\right)v\\ (I_z-N_{\dot{r}})\dot{r}=-(X_{\dot{u}}-Y_{\dot{v}})uv+(N_r+N_{r|r|}|r|)r+N\end{cases} \tag{10}$$

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]:

$$
\begin{aligned}
&M = M_R + M_A \\
&M_A = diag\{X_{\dot{u}}, Y_{\dot{v}}, Z_{\dot{w}}, K_{\dot{p}}, M_{\dot{q}}, N_{\dot{r}}\} \\
&= diag\{4.09, 4.09, 4.09, 0, 0.0554, 0.0629\} \\
&M_R = diag\{m, m, m, I_x, I_y, I_z\} \\
&= diag\{3.58, 3.58, 3.58, 0, 0, 0.0075\} \\
&D(V) = diag\{X_u, Y_v, Z_w, K_p, M_q, N_r\} \\
&= diag\{9.78, 9.78, 9.78, 1.22, 1.22, 1.22\}
\end{aligned}
$$

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 μ 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 $P(\xi_P(\mu), \eta_P(\mu), 0)$ on path is uniquely determined by parameter μ. Then μ can represent the arc length of the path of the curve to be tracked, c(μ) represents the curvature at any point in the path. Define tracking error $\psi_e = \psi_w - \psi_F$. The path tracking error of spherical amphibious robot under horizontal kinematics equation can be obtained[14].

$$
\begin{cases}
\dot{x}_e = y_e c(\mu)\dot{\mu} + u\cos\psi_e - \dot{\mu} \\
\dot{y}_e = -x_e c(\mu)\dot{\mu} + u\sin\psi_e \\
\dot{\psi}_e = r + \dot{\beta} - c(\mu)\dot{\mu}
\end{cases}
\tag{11}
$$

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*

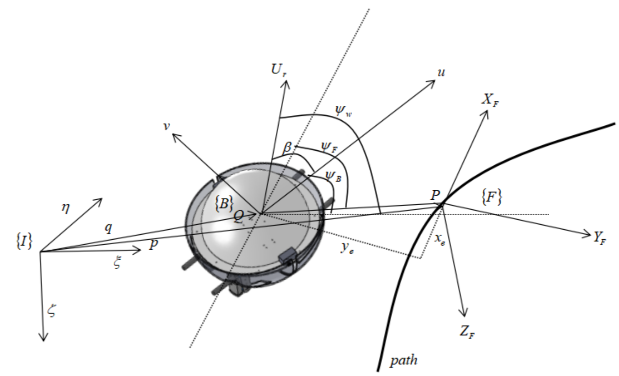

Fig.3 Sketch of Horizontal Path Tracking for the Robot

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, $f(\bullet)$is the external interference factor.

$$
\begin{cases}
\dot{\psi} = r \\
\dot{r} = -\dfrac{(X_{\dot{u}} - Y_{\dot{v}})}{(I_z - N_{\dot{r}})}uv + \dfrac{(N_r + N_{r|r|}|r|)}{(I_z - N_{\dot{r}})}r + \\
\dfrac{N}{(I_z - N_{\dot{r}})} + \dfrac{f_r}{(I_z - N_{\dot{r}})}
\end{cases}
\tag{12}
$$

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

$$z_1 = \psi - \psi_d \tag{13}$$

So

$$\dot{z}_1 = \dot{\psi} - \dot{\psi}_d = r - \dot{\psi}_d \tag{14}$$

A new state variable z2 is introduced here.:

$$\dot{z}_1 = z_2 - \alpha \tag{15}$$

Where $k_1>0$, take $\alpha = k1 \cdot z1$,we can get

$$z_2 = r + k_1 z_1 - \dot{\psi}_d \tag{16}$$

Define Lyapunov function:

$$V_1 = \frac{1}{2}z_1^2 \tag{17}$$

So

$$
\begin{aligned}
\dot{V}_1 &= z_1\dot{z}_1 = z_1(r - \dot{\psi}_d) \\
&= z_1(z_2 - k_1 z_1) = z_1 z_2 - k_1 z_1^2
\end{aligned}
\tag{18}
$$

The following sliding surface is designed:

$$S_1 = c_1 z_1 + z_2 \tag{19}$$

Define Lyapunov function:

$$V_2 = V_1 + \frac{1}{2}S_1^2 \tag{20}$$

We can get

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + S_1\dot{S}_1 \\ &= -k_1 z_1^2 + z_1 z_2 + S_1\dot{S}_1 \\ &= -k_1 z_1^2 + z_1 z_2 + S_1(c_1\dot{z}_1 + \dot{z}_2) \\ &= -k_1 z_1^2 + z_1 z_2 + S_1(c_1\dot{z}_1 + \dot{r} - \dot{\alpha}) \\ &= -k_1 z_1^2 + z_1 z_2 + S_1(c_1\dot{z}_1 - \frac{(X_{\dot{u}} - Y_{\dot{v}})}{(I_z - N_{\dot{r}})}uv + \\ &\frac{(N_r + N_{r|r|}|r|)}{(I_z - N_{\dot{r}})}r + \frac{N}{(I_z - N_{\dot{r}})} + \frac{f_r}{(I_z - N_{\dot{r}})} + \dot{\alpha} - \ddot{\psi}_d)\end{aligned} \tag{21}$$

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 .

$$\tilde{f}_r = f_r - \hat{f}_r \tag{22}$$

Where (22) is the estimation error of external interference f_r . Define Lyapunov function:

$$V_3 = V_2 + \frac{1}{2\gamma_1}\tilde{f}_r^2 \tag{23}$$

So

$$\begin{aligned}\dot{V}_3 &= \dot{V}_2 + \frac{1}{\gamma_1}\tilde{f}_r\dot{\tilde{f}}_r \\ &= \dot{V}_2 + \frac{1}{\gamma_1}\tilde{f}_r\left(\dot{f}_r - \dot{\hat{f}}_r\right) \\ &= \dot{V}_2 - \frac{1}{\gamma_1}\tilde{f}_r\dot{\hat{f}}_r \\ &= -k_1 z_1^2 + z_1 z_2 + \\ &S_1\left(\begin{aligned}&c_1\dot{z}_1 - \frac{(X_{\dot{u}} - Y_{\dot{v}})}{(I_z - N_{\dot{r}})}uv + \frac{(N_r + N_{r|r|}|r|)}{(I_z - N_{\dot{r}})}r \\ &+ \frac{N}{(I_z - N_{\dot{r}})} + \frac{\hat{f}_r}{(I_z - N_{\dot{r}})} + \dot{\alpha} - \ddot{\psi}_d\end{aligned}\right) \\ &- \frac{1}{\gamma_1}\tilde{f}_r\left(\dot{\hat{f}}_r - \gamma_1 S_1\right)\end{aligned} \tag{24}$$

The course angle controller is designed as follows:

$$N = (I_z - N_{\dot{r}})\left[\begin{aligned}&\frac{(X_{\dot{u}} - Y_{\dot{v}})}{(I_z - N_{\dot{r}})}uv - \frac{(N_r + N_{r|r|}|r|)}{(I_z - N_{\dot{r}})}r - c_1\dot{z}_1 - \\ &\dot{\alpha} + \ddot{\psi}_d - \frac{\hat{f}_r}{(I_z - N_{\dot{r}})} - h_1(S_1 + \varepsilon_1 \operatorname{sgn}(S_1))\end{aligned}\right] \tag{25}$$

The adaptive law as follows:

$$\dot{\hat{f}}_r = \gamma_1 S_1 \tag{26}$$

It can be obtained from the heading angle controller and the adaptive law:

$$\dot{V}_3 = -k_1 z_1^2 + z_1 z_2 - h_1 S_1{}^2 - h_1\varepsilon_1|S_1| \tag{27}$$

We can take

$$Q_1 = \begin{bmatrix} k_1 + h_1 c_1^2 & h_1 c_1 - \frac{1}{2} \\ h_1 c_1 - \frac{1}{2} & h_1 \end{bmatrix} \tag{28}$$

Because

$$\begin{aligned} z^T Q_1 z &= [z_1 z_2]Q_1 \\ &= k_1 z_1^2 - z_1 z_2 + h_1 S_1^2 \end{aligned} \tag{29}$$

So we can be written as

$$\dot{V}_3 \le -z^T Q_1 z - h_1\varepsilon_1|S_1| \tag{30}$$

Then

$$\begin{aligned} |Q_1| &= h_1(k_1 + h_1 c_1^2) - \left(h_1 c_1 - \frac{1}{2}\right)^2 \\ &= h_1(k_1 + c_1) - \frac{1}{4} \end{aligned} \tag{31}$$

By choosing the appropriate value of h_1,c_1,k_1 it can make|Q|>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:

$$\begin{aligned}\dot{u} &= \frac{(m - Y_{\dot{v}})}{(m - X_{\dot{u}})}vr + \frac{(X_u + X_{u|u|}|u|)}{(m - X_{\dot{u}})}u \\ &+ \frac{X}{(m - X_{\dot{u}})} + \frac{f_u}{(m - X_{\dot{u}})}\end{aligned} \tag{32}$$

According to the design method of course angle controller, the speed tracking controller can be obtained as follows:

$$\begin{aligned} X &= -(m - Y_{\dot{v}})vr - (X_u + X_{u|u|}|u|)u + (m - X_{\dot{u}})\cdot \\ &\dot{u}_d - \hat{f}_u - (m - X_{\dot{u}})h_2(S_2 + \varepsilon_2 \operatorname{sgn}(S_2))\end{aligned} \tag{33}$$

The adaptive control law is designed as follows[18]:

$$\dot{\hat{f}}_u = \gamma_2 S_2 \tag{34}$$

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 simulation .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 ξ(0)=10m,η(0)=0;the initial velocity is u(0)=v(0)-=r(0)=0m/s;the initial attitude angle is ψ(0)=π/2; the desired longitudinal velocity is u_d=0.1m/s.

The time-varying external disturbances are as follows:

$$\begin{aligned} f_u &= 0.5*\cos(t) \\ f_r &= 0.5*\sin(t) \end{aligned} \tag{35}$$

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

$$\xi_p = \mu, \quad \eta_p = 2\sin[(2\pi/10)*\mu]$$

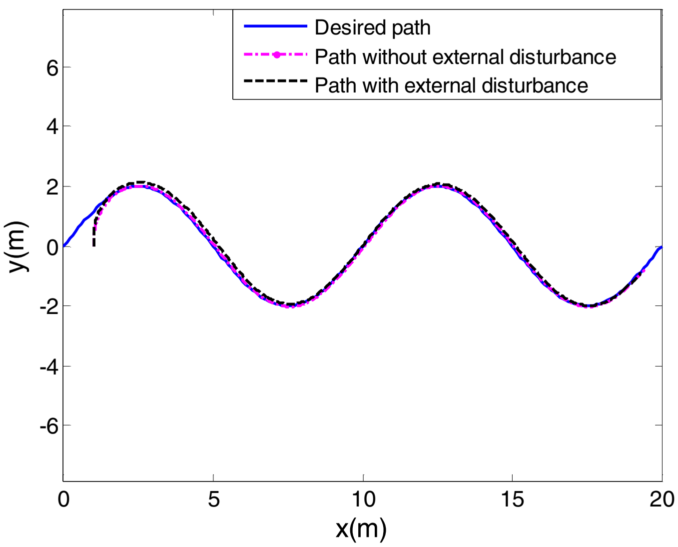

Fig.4 Sinusoidal path tracking

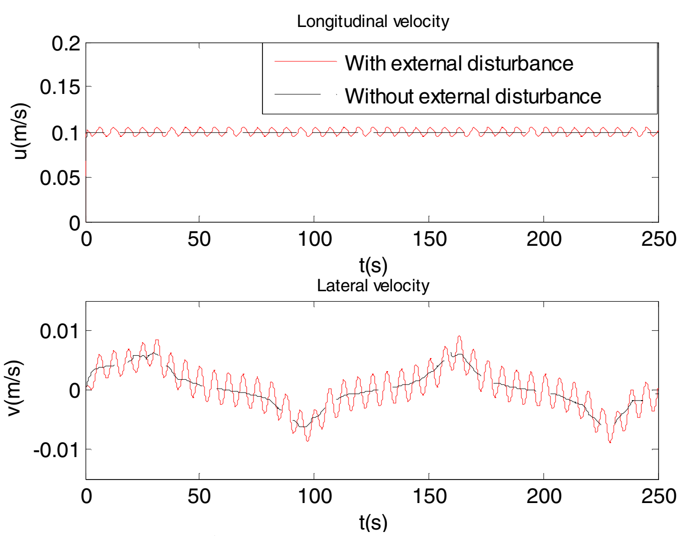

Fig.5 Linear velocity response curve

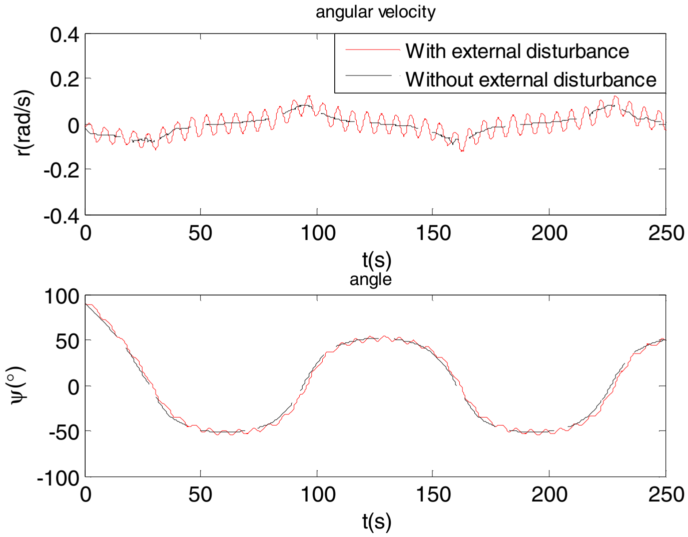

Fig.6 Angular velocity and angular response curve

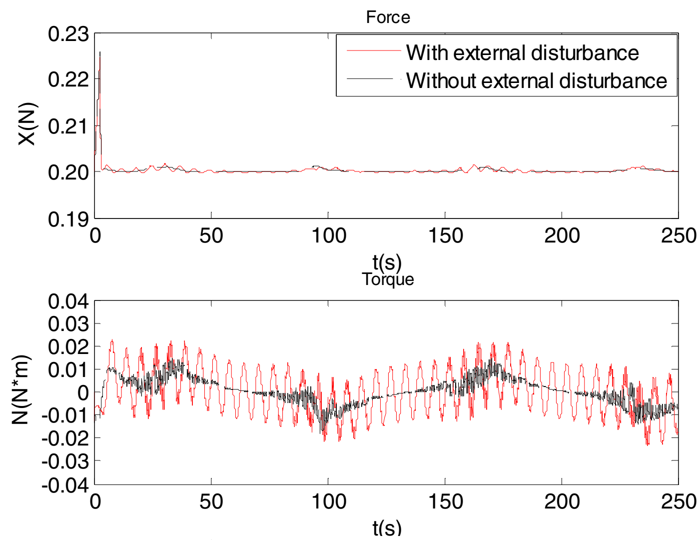

Fig.7 Force and Torque response curve

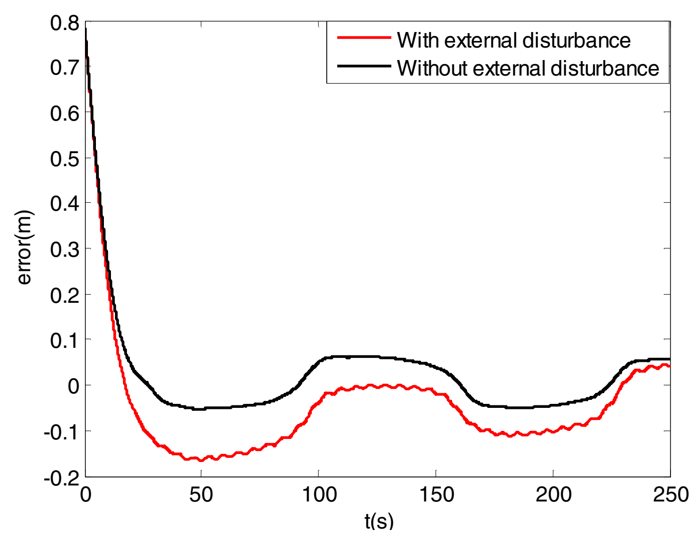

Fig.8 Path tracking error

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 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 Fig. 6 also changes with the path, which accords with the actual situation of sinusoidal path of spherical amphibious robot.In Fig.7, the longitudinal thrust stability of the spherical amphibious robot is 0.2N and the steering moment changes with the path.The tracking error model is established in the Serret-Frenet coordinate system. Fig.8 shows the path tracking error. Under the action of the controller, the position error also converges rapidly, and the maximum displacement error does not exceed 0.2 meters.From the simulation results, 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.

Acknowledgments

This research is supported by National Natural Science Foundation of China (61703305), Key Research Program of the Natural Science Foundation of Tianjin (18JCZDJC38500) and Innovative Cooperation Project of Tianjin Scientific and Technological (18PTZWHZ00090).

References

[1] Duan Longfei., “Fin Source Technology "FiFish Flying Fish",” *Appears.Robot Technology and Application*,vol.38,no.21,pp.8-8,2016.

[2] http://tech.huanqiu.com/gundong/2016-03/8769665.html?agt=15438.

[3] Packard G E , Austin T , Christenson R , “Servo controlled rapid MCM target reacquisition using REMUS-100”.*Oceans. IEEE*,pp.14-19,2014.

[4] Govindarajan A F, Pineda J, Purcell M, “Species- and stage-specific barnacle larval distributions obtained from AUV sampling and genetic analysis in Buzzards Bay, Massachusetts, USA”. *Journal of Experimental Marine Biology & Ecology*,vol.472,no.27,pp.158-165,2015

[5] Packard G E , Kukulya A , Austin T , “Continuous autonomous tracking and imaging of white sharks and basking sharks using a REMUS-100 AUV”. *Oceans. IEEE*, pp.213-219,2013.

[6] Yang Ning. “Scientists Build Jellyfish Machine Spy”. *Science Grand View Garden*,vol.31,no.13,pp.34-35,2013.

[7] Yanlin He, Lianqing Zhu, Guangkai Sun, Junfei Qiao, Shuxiang Guo, “Underwater motion characteristics evaluation of multi amphibious spherical robots”, *Microsystem Technologies*, vol.25, No.2, pp.499-508, 2019.

[8] Liang Zheng, Shuxiang Guo, Shuoxin Gu, “The communication and stability evaluation of amphibious spherical robots”, *Microsystem Technologies*, vol.24, pp.1-12,2018

[9] ShuxiangGuo,YanlinHe,LiweiShi,ShaowuPan,RuiXiao,KunTangabPing, “Modeling and experimental evaluation of an improved amphibious robot with compact structure”. *Robotics and Computer-Integrated Manufacturing,*vol.51,pp.37-52,2018.

[10]MansourKarkoub,Hsiu-MingWu,Chih-LyangHwang.”Nonlinear trajectory-tracking control of an autonomous underwater vehicle”,*Ocean Engineering*,vol.145,no.15,pp.188-198,2017.

[11]Bian Jingwei, Xiang Ji “QUUV: A quadrotor-like unmanned underwater vehicle with thrusts configured as X shape” . *Applied Ocean Research*, vol.78,no.30,pp.201-211,2018.

[12]Zaopeng Dong, Lei Wan, Yueming Li,”Trajectory tracking control of underactuated USV based on modified backstepping approach”.*International Journal of Naval Architecture and Ocean Engineering*,vol.7,no.5,pp.817-832,2015

[13] Bi Lin. “Gait planning and motion analysis based on spherical amphibious robots”. Tianjin University of Technology, 2016.

[14]Li-JunZhang,He-MingJia,Da-PengJiang,”Sliding Mode Prediction Control for 3D Path Following of An Underactuated AUV”,*IFAC Proceedings Volumes*,vol.47,no.3,pp.8799-8804,2014.

[15] Gao Jian, “Adaptive Nonlinear Control Technology for Unmanned Underwater Vehicles, Northwest Polytechnic University Press”, 2016.

[16]Zhou Jiajia, Yan Zeping, “Unmanned Underwater Vehicle Control Technology”, *National Defense Industry Press*, 2015.

[17]J.Guerrero,J.Torres,V.Creuze,A.Chemori,”Trajectory tracking for autonomous underwater vehicle: An adaptive approach”,*Ocean Engineering*,vol.172,no.15,pp.511-522,2019.

[18] F.Rezazadegan,K.Shojaei,F.Sheikholeslam, “A novel approach to 6-DOF adaptive trajectory tracking control of an AUV in the presence of parameter uncertainties”.*Ocean Engineering*,vol.107,no.1,pp.246-258,2015.