RBF neural network sliding mode control on pitching motion of an underwater spherical vehicle

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Abstract: The pendulum spherical underwater vehicle can realize the ascending and descending motion in water by using the internal pitch pendulum and the central propeller. It is the frequent swing of the pitch pendulum that causes the fluctuation of the speed of the robot and reduces the stability of the system. A two-stage sliding method is proposed for the pitch driving characteristics of the robot and it can control the pitch angle and the swing angle of the pitch pendulum of the robot at the same time. The neural network is introduced to compensate the interference items adaptively. The stability of the designed controller is proved in theory. The simulation and experimental results show that the proposed control method can realize the rapid control of the pitch angle of the robot and the frequency of the pitch pendulum. The complex swing is restrained effectively, and the stability of the underwater motion of the robot is improved.

1. Introduction
Miniature underwater vehicle is a hotspot of research in recent years. On the one hand, it is playing a key role in different kinds of applications, such as scientific, commercial and military and so on. It is convenient for underwater exploration and data acquisition. On the other hand, it has the advantages of low noise and good concealment, and can carry out military tasks such as water investigation and assault. The consideration underwater vehicle uses the heavy pendulum and flywheel to regulate the attitude, which is flexible, stability and time saving. But when pitching, a slight oscillation phenomenon of the heavy pendulum will appear which will affect the regular movement in accelerating and pitching. To suppress the coupling fluctuation and improve the stability of the robot, we have conducted many studies. In our previous work, we have proposed a fluctuation suppression method by controlling the propeller thrust at the cost of changing the surge velocity frequently and we have studied the influence of the heavy pendulum’s length and weight on the oscillation.

The Variable structure control (VSC) is a discontinuous control method and the sliding mode control (SMC) is the main mode of it[1]. The SMC method can realize Finite-time convergence and it is low sensitivity to matched parameter uncertainty but the chattering problem is a weakness. To alleviate the chattering, many control schemes have been proposed. In [2], a class of nonlinear systems are controlled by using neural networks to compensate the weakness of SMC. In [3], a hierarchical fuzzy SMC method was proposed to control the swing bridge system, which achieved decoupling control for under actuated system, in [4, 5], an anti-swing fuzzy logic controller for an overhead crane with hoist was designed. In [6], a continuous homogeneous sliding-mode control algorithm was proposed for uncertain systems. In [7], a fuzzy hierarchical sliding mode controller was proposed for
inverted pendulum–cart system. In [8], high order sliding mode controller for hypersonic vehicle which could reduce chattering was proposed. In this paper, a hierarchical sliding mode control structure based on neural network is proposed, in which the RBF neural networks compensate the uncertainty term. The control method ensures the stability of the pitch angle and the inhibition of heavy pendulum swinging.

2. Design of the pitching controller

Table 1. Parameters of the robot

| Notion of parameter       | Symbol of parameter | Value of parameter |
|---------------------------|---------------------|--------------------|
| Thrust                    | $T$                 | (-20N, 20N)        |
| Torque                    | $M$                 | (-20N·m, 20N·m)    |
| Quality of shell          | $m_1$               | 30kg               |
| Quality of heavy pendulum | $m_2$               | 30kg               |
| Inertia of spherical shell| $I_y$               | 2kg·m²             |
| Resistance coefficient    | $C_d$               | 15                 |
| Additional mass           | $\lambda$           | 15kg               |
| Swing angle               | $\alpha$            | $(-\pi/2, \pi/2)$ |
| Pitching angle            | $\theta$            | $(-\pi/2, \pi/2)$ |

For a real control system, stability is the predominant character, the underwater tasks need the robot to adjust its pitching angle frequently with a constant surge velocity. But the oscillation of the heavy pendulum may cause instability of the robot, and the oscillation will occupy the limited space within the robot. So, it is necessary to suppress the undesirable oscillations, to realize this object, a controller for suppressing oscillation is designed. The dynamic equation (5) is transformed into system (9), which is an underactuated system.

$$\begin{align*}
\dot{\alpha} &= \frac{(m_1 + m_2 + \lambda)(M - m_2 gl \sin \alpha) + m_2 \lambda T \cos(\alpha + \theta) - C_m m_2 lu \sin(\alpha + \theta) - C_x w \sin(\alpha + \theta) - (m_1 + \lambda) \left(\omega \theta \cos(\alpha + \theta) - u \dot{\theta} \sin(\alpha + \theta)\right)}{I(m_1 + \lambda)} \\
\dot{\theta} &= \frac{M}{I_y}
\end{align*}$$

(1)

2.1 Sliding Mode Decoupling Control

In order to keep the stability of the system, the oscillation of the heavy pendulum must be suppressed quickly and the robot’s pitching angle must reach desired value accurately. However, there only one control input $M$. Here the pitching angle and its velocity, the swing angle and its velocity are selected as the state variables. In order to design the primary sliding surface let, the system (9) considering the external random disturbances is decomposed into the following two subsystems:

$$\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= b_1 \tau \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= f(x_3) + b_2 \tau + D
\end{align*}$$

(2)  (3)

Where
\[
\tau = M \\
\dot{b}_1 = \frac{1}{I} \\
\dot{b}_2 = \frac{m_1 + m_2 + \lambda}{m_1 l^2 (m_1 + \lambda)} \\
f(x_1) = \frac{-g \sin(\alpha(m_1 + m_2 + \lambda))}{l(m_1 + \lambda)} \\
D = \frac{T \cos(\alpha + \theta) \cdot C_d (u|u| \cos(\alpha + \theta) + w|w| \sin(\alpha + \theta)) - (u \theta \cos(\alpha + \theta) - u \dot{\theta} \sin(\alpha + \theta))}{l(m_1 + \lambda)}
\]

Subsystem 1 is the dynamical equations for pitching motion, \( \theta_d \) is the desired pitching angle let \( e_1 = \theta - \theta_d \), \( \dot{e}_1 = \dot{\theta} - \dot{\theta}_d \), define the first level sliding surface \( s_1, s_2 \) for the two subsystems respectively as follows:

\[
s_1 = c_1 \dot{e}_1 + \dot{e}_1 \\
\dot{s}_1 = c_1 \dot{e}_1 + \dot{e}_1 = c_1 \dot{\theta} - c_1 \dot{\theta}_d + b_1 \tau - \ddot{\theta}_d 
\]

Subsystem 2 is the oscillation dynamical equations of the pendulum in X-Z plane. In order to eliminate the oscillation phenomenon, the heavy pendulum should be regulated in a vertical line (\( \alpha = 0 \)), define sliding surface 2 of subsystem 2 as follows:

\[
s_2 = c_2 \alpha + \dot{\alpha} \\
\dot{s}_2 = c_2 \dot{\alpha} + \dot{\alpha} = c_2 \dot{\theta}_d + b_2 \tau + D 
\]

To guarantee the convergence of subsystems, we can choose the ultimate sliding surface as follows:

\[
S = \beta S_1 + (1 - \beta) S_2 \\
\dot{S} = \beta \dot{S}_1 + (1 - \beta) \dot{S}_2
\]

\[
= \beta (c_1 \dot{e}_1 + \dot{e}_1) + (1 - \beta) (c_2 \dot{\theta}_d + b_1 \tau + D)
\]

\[
= \beta (c_1 \dot{e}_1 + \dot{e}_1) + (1 - \beta) (c_2 \dot{\theta}_d + f(\alpha)) + (\beta b_1 + b_2 - \beta b_2) \tau + (1 - \beta) D
\]

To guarantee the convergence of the ultimate sliding surface, the controllers are taken as:

\[
\tau = \frac{\beta (c_1 \dot{e}_1 + \dot{e}_1) - (1 - \beta) (c_2 \dot{\theta}_d + f(\alpha)) - (1 - \beta) D}{\beta b_1 + b_2 - \beta b_2}
\]

2.2 Neural Network Estimation

To improve the performance of the system and alleviate the chattering, the most useful property of NNs in control theory is their learning ability in approximating a nonlinear function, this paper we use the RBF neural network technique to compensate these uncertainties and improve the robustness of the system, and its approximation performance plays an important role in compensating interference:

\[
\begin{align*}
D &= W^T h(x) + \varepsilon \\
h(x) &= \exp \left( \frac{\|x - c_j\|^2}{2 b_j^2} \right)
\end{align*}
\]

Where \( W \) is the RBF network optimal parameters of output weight; \( \varepsilon \) is the network approximation error; \( c_j \) and \( b_j \) are the optimal parameters for the Gaussian function.

Let \( x = [\alpha, \dot{\alpha}] \) be the neural network input, and the output can be as follow :

\[
\hat{D} = f(\hat{W}, x, \hat{c}, \hat{b})
\]

where \( \hat{D} \) is network output’s compensation value. \( \hat{W}, \hat{c}, \hat{b} \) are the estimation value of the network parameters. We can get the the error between the system uncertainty and the output of the neural network:
\[
\begin{align*}
\dot{\hat{b}} &= D - \hat{b} \\
\dot{\hat{w}} &= w' - \hat{w} \\
\dot{\hat{c}} &= c' - \hat{c} \\
\hat{b} &= \hat{b'} - \hat{b}
\end{align*}
\] (12)

The adaptive rate of the three variable parameters can be adjusted according as follows:

\[
\begin{align*}
\dot{\hat{w}} &= \frac{(1 - \beta) \frac{\partial f}{\partial \hat{w}} S}{\gamma_1 (\beta b_1 + b_2 - \beta b_2)} \\
\dot{\hat{c}} &= \frac{(1 - \beta) \frac{\partial f}{\partial \hat{c}} S}{\gamma_2 (\beta b_1 + b_2 - \beta b_2)} \\
\dot{\hat{b}} &= \frac{(1 - \beta) \frac{\partial f}{\partial \hat{b}} S}{\gamma_3 (\beta b_1 + b_2 - \beta b_2)}
\end{align*}
\] (13)

3. Control Simulation Experiment

To test the effectiveness of the designed pitch control, the RBF neural network is designed with 2 nodes in input layer, 10 nodes in hidden layer and 1 node in output layer. \(c_1=0.8, \ c_2=18, \ \beta=0.8, \ \gamma_i=1; i=1,2,3,4\). The other parameters are set in accordance with Table 1. The control results are shown in Figure 1,2.

![Figure 1 Swing angle](image1)

![Figure 2 Horizontal velocity](image2)

From the simulation results, it can be seen the proposed control scheme realize an excellent dynamic performance for pitching movement of the underwater robot. The oscillation angle is suppressed and converged to zero quickly.

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