Backstepping Sliding Mode Hover Control Based on Nonlinear Disturbance Observer for Spherical Robot

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Abstract. Aiming at the hovering control problem of spherical robot used in transformer internal detection, a Backstepping sliding mode control method based on nonlinear disturbance observer was proposed to estimate and compensate the interference in robot motion direction. Firstly established the robot motion model, then the disturbance observer was constructed according to the system state equation, and the inverse sliding mode controller was proposed based on the Lyapunov stability theory. The simulation results showed that the designed nonlinear disturbance observer can effectively reduce the instability caused by the external disturbances in the horizontal and depth directions during the hovering process of the robot, it has strong robustness.

Introduction

Transformer internal inspection robot is a micro spherical robot which can enter the transformer internal for fault detection directly, it equipped with camera, lighting, depth gauge and attitude sensor, can be used to film the fault condition of oil-immersed transformer, such as the inner winding deformation and insulation degradation, and the internal image real-time transmission to the control side, the realization of transformer internal fault accurate identification.

The robot is spherical in shape and structure, propelled by 6 channel injection pumps, capable of 4-dof operation, with zero turning radius and flexible movement [1,2,3,4,5]. It is very suitable for the complex environment with such special structure inside the transformer and narrow area.

For underwater robot's motion control problems, the researchers conducted a lot of research and put forward a variety of adaptive control methods, such as fuzzy control, sliding mode control, neural network control and a variety of control mode combined with compound control method, etc., to a certain extent solved the error due to such as modeling, hydrodynamic parameter uncertainty caused by the robot control problems. A neural network cerebellar model definition control (CMAC) and a fuzzy controller is respectively adopted to optimize the design of the PID controller of AUV in [6,7], which enhanced the stability and anti-interference of the controller. For the AUV motion control problem with non-complete constraints, the point stabilization control model of AUV is established based on decoupling transformation, inverse step control, power integral, logic control and other methods in [8,9,10,11], and the global asymptotic stability of AUV is effectively achieved; In [12], taking into account of unknown disturbance factors of nonlinear system, a dynamic disturbance compensator is introduced to design the sliding mode controller, which realized the motion control of AUV. In [13], the AUV three-dimensional path tracking sliding mode controller is designed by using feedback correction and Backstepping optimization, which has good tracking performance. In [14], a fuzzy sliding mode controller is designed, which effectively improves the stability and robustness of AUV.

Although the above controllers have relatively good control performance, the complexity of the controllers is not suitable for direct application of the underlying control of the robot, and there is still no optimal control method for the precise motion control of the micro-underwater robot in the
complex environment. As the diameter of the transformer detect spherical robot is only 150mm, any external disturbance or control error will greatly affect the robot's motion control effect. This paper aims to solve the hovering control problem of the miniature spherical robot under unknown interference. According to the movement characteristics of spherical robot and the special application environment, based on the Backstepping and sliding mode theory to design a kind of controller applicable to the control the heading angle and depth of the spherical robot, with the introduction of unknown nonlinear disturbance observer to compensate real-time outside interference. Simulation and experimental results show that the control system can convergence fast and stably, and effectively restrain the horizontal motion and outside interference caused by unknown disturbance. It can effectively achieve the robot hovering movement, has the merit of strong stability.

**Problem Description**

Transformer oil is a fluid with good fluidity [15]. The force on robot in oil can be referred to the analysis of underwater robot in water. The attitude control of the spherical robot is realized by 6 channel injection pumps which are installed in the middle of the sphere. The overall structure of the robot is shown in figure 1.

![Figure 1. The internal structure of the robot.](image)

When the robot is applied in practice, the system motion is disturbed by external collision, adding the disturbance terms to the system dynamics equation, and ignore the higher-order term of the third order or above in the equation, then the dynamic model of the vertical movement of the robot is obtained as follows:

\[
\begin{align*}
(I - N_r) \ddot{r} - N_r \dot{r} - N_v \dot{v} &= T_\phi + \Delta f_N \\
(m - Z_w) \ddot{w} &= Z_w w + T_z + \Delta f_z
\end{align*}
\]

(1)

Where, \( m \) is the mass of the spherical robot, \( I \) is the moment of inertia of the relative motion coordinate system \( z \); \( w \) is the velocities of the robot along the \( z \) axes; \( r \) is the angular velocities along the \( z \) axes. \( T_\phi \) is the pushing torque of the \( z \) axis, \( N_v \) and \( Z_w \) are fluid damping coefficient, \( \theta \) and \( \phi \) are the angle between the fixed coordinate system and the carrier coordinate system between the vertical plane and the horizontal plane. \( T_z \) is the thrust of the \( z \) axis, \( \Delta f_z \) and \( \Delta f_N \) are uncertain disturbance terms.

**Controller Design**

The state equation of the nonlinear controller is defined as:
Where \( A \) and \( B \) are known nonlinear parametric equations and \( d \) are unknown external disturbances.

Due to the narrow space inside the transformer, the robot will inevitably collide with operation, causing the robot to oscillate. At the same time, the transformer oil disturbance and control error caused by motion will also cause the robot control difficulty. In order to ensure that the spherical robot can effectively achieve accurate motion control under external interference, the nonlinear disturbance observer is introduced to track and estimate the interference.

**Nonlinear Disturbance Observer Design**

According to the system state equation (2), the state form of nonlinear disturbance observer is defined:

\[
\begin{align*}
g &= \hat{d} - p(x) \\
\dot{g} &= -L(x)g + L(x)(-p(x) - Bu - Ax) \\
\end{align*}
\]

Where \( \dot{p}(x) = L(x)\hat{x} \), \( L(x) \) is the design parameters, define \( L(x) > 0 \).

Define observer error \( \hat{d} = d - \hat{d} \), since there is no differential prior information on the disturbance term \( d(x) \), for the convenience of analysis, when the disturbance changes relative to the observer's dynamic characteristics are assumed, the observation dynamic error equation can be known according to equation (7)

\[
\dot{\hat{d}} = \dot{d} - \ddot{d} = -\dot{g} - \dot{p}(x) = -L(x)\ddot{d}
\]

Consider nonlinear disturbance observer Lyapunov function:

\[
V_{dis} = \frac{1}{2} \hat{d}^2
\]

Then \( \dot{V}_{dis} = \hat{d} \ddot{d} = -L(x)\hat{d}^2 \), which means the observer is globally asymptotically stable. The control output of nonlinear disturbance observer is:

\[
u_d = \frac{1}{B} \hat{d}
\]

**Backstepping Sliding Mode Controller Design**

After the introduction of nonlinear disturbance observer, the system state equation (2) can be described as:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= Ax + Bu + \hat{d} \\
\end{align*}
\]

Design \( z_d \) as the target depth, defined \( x_i \) as the actual depth, and the system tracking error can be described as:

\[
\begin{align*}
e_1 &= x_i - z_d \\
e_2 &= x_2 - \alpha_i \\
\end{align*}
\]

Define virtual controls:
\[
\alpha_t = -k_t e_t + \dot{z}_d
\]
Where \( k_t > 0 \) is the feedback gain. Then
\[
\dot{e}_t = -k_t e_t + e_2
\]
(10)
Consider Lyapunov function
\[
V_1 = \frac{1}{2} e_1^2
\]
(11)
Then
\[
\dot{V}_1 = e_t \dot{e}_t = e_t (x_2 - \ddot{z}_d) = e_2 (e_1 + \alpha_t - \ddot{z}_d)
\]
(12)
Substitute equation (13) into equation (15):
\[
\dot{V}_t = -k_t e_1^2 + e_1 e_2
\]
(13)
If \( e_2 = 0 \), then \( \dot{V}_1 \leq 0 \).
Furthermore, the switching function of sliding surface is defined as:
\[
s = c_1 e_t + e_2
\]
(14)

Where \( c_1 > 0 \).
Since \( \dot{e}_t = -k_t e_t + e_2 \), then
\[
s = c_1 e_t + \dot{e}_t + k_t e_t = (c_1 + k_t) e_t + \dot{e}_t
\]
(15)
Obviously, if \( s = 0 \), then \( e_t = 0, ~ e_2 = 0, ~ \dot{V}_1 \leq 0 \). Design controller:
\[
u = B^{-1} (-c_1 (z_2 - k_t z_1) - A(z_2 + \ddot{z}_d - k_t z_1) - D \text{sgn}(s) + \dot{z}_d - k_1 \dot{z}_1 - h(s + \beta \text{sgn}(s)))
\]
(16)
Where \( h \) and \( \beta \) are positive constant.
Considering the disturbance estimation of nonlinear disturbance observer, the input control law of the controlled system is:
\[
u = u_{by} - u_d
\]
(17)

**Simulation**

Based on the above analysis, \( u_w \) and \( u_r \) of the robot horizontal heading Angle controller are respectively:
\[
\begin{align*}
    u_w &= B_w^{-1} (-c_{w1} (z_{w2} - k_{w1} z_{w1}) - A_w (z_{w2} + \ddot{z}_{wd} - k_{w1} z_{w1}) + \ddot{z}_{wd} - k_{w1} \dot{z}_{w1} - h_w s_w - \hat{f}_{dw}(s)) - u_{dw} \\
    u_r &= B_r^{-1} (-c_{r1} (z_{r2} - k_{r1} z_{r1}) - A_r (z_{r2} + \ddot{z}_{rd} - k_{r1} z_{r1}) + \ddot{z}_{rd} - k_{r1} \dot{z}_{r1} - h_r s_r - \hat{f}_{dr}(s)) - u_{rw}
\end{align*}
\]
(18)
Where \( u_{dw} \) and \( u_{rw} \) are the estimates of external disturbances.

The miniature spherical robot has a mass of 1.312kg, and the diameter of the sphere \( R=150\text{mm} \).
The parameters of the nonlinear disturbance observer were chosen as: \( L(x)=20 \), and \( p(x)=20x_2 \).
Inverse controller parameter \( k_1=8 \); The initial depth and initial vertical velocity of the system is 0.
Set the depth direction of the system has time-varying interference:
\[ d = \begin{cases} 0, & 0 < t \leq 20s \\ 2\sin(t/20), & 20 < t \leq 100s \end{cases} \]

There is time-varying interference in the horizontal direction

\[ d = \begin{cases} 0, & 0 < t \leq 80s \\ 20, & 80 < t \leq 120s \\ 20\sin(t/10), & 120 < t \leq 200s \end{cases} \]

(19)

(20)

The estimated values of external interference and interference observer are shown in figure 2.

Set the goal of depth and course angle respectively as real-time curve \( z_d = 0.5+0.5\sin(t/10) \text{m/s} \) and fixed value 180 °, the figure 3 shows that the controller added disturbance observer can less affected by external interference, it can adjust output compensation in time when realizing depth tracking, the tracking error is not more than 2 cm; Meantime the angle controller can convergence rapidly, with almost no overshoot phenomenon, and the angle control system affected by disturbance is small, the adjusting error is less than 1 ° after stabilized; The system fully realizes the hovering control.

![Figure 2. External interference and observed interference values.](image1)

![Figure 3. Robot depth simulation diagram with interference observer.](image2)

However, the controller without disturbance observer is shown in figure 4. When the system changes the depth of the target in real time, the controller cannot effectively track the depth of the target. After the system is disturbed, the control effect becomes significantly worse. System course target for fixed value are greatly influenced by mutation interference, the controller cannot effectively adjust back to the target angle, with maximum interference error 11 °
Based on the above simulation results, when the system has unknown interference, the designed disturbance observer can track the external interference in real time, effectively compensates the disturbance caused by external interference, reduce the jitter problem of the controller, and improve the control performance significantly.

**Conclusion**

In this paper, a nonlinear disturbance observer is introduced to compensated external interference, the depth and heading angle controller of the robot are designed based on Backstepping and sliding mode control method. Simulation results show that the controller can effectively approach the system disturbance, and reduce the disturbance quantity of the controlled system, quickly reach the target depth and heading angle, finally realize the hover control of the robot. The designed controller has good tracking performance, effectively solves the controller jitter caused by disturbance, enhances the system robustness. It is suitable for the working environment of the spherical robot.

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