Sliding Mode Steering Control of Spherical Underwater Robot

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Abstract: From the point of view of motion control, considering the effects of inertia mass, additional mass, secondary resistance, gravity and buoyancy on the robot, a relatively complete dynamic model of the spherical underwater vehicle is established. On this basis, the steering controller of the spherical underwater vehicle is designed based on the principle of sliding mode exponential reaching law. The control performance is compared with that of ordinary PID control algorithm. From the simulation results, it can be seen that the steering control of the spherical underwater vehicle with the designed sliding mode control method can make the robot have faster steering ability and stronger anti-jamming ability.

1. Introduction

The types of underwater vehicles are mainly divided into cylindrical slender underwater vehicle, frame underwater vehicle and spherical underwater vehicle[1]. Among them, spherical underwater vehicle has obvious advantages in compression resistance and steering performance compared with the first two[2]. The shape of spherical underwater vehicle has perfect symmetry, and the spherical perfect circular design can endure huge underwater pressure. At present, most of the research on spherical underwater vehicles is still in the stage of linear and depth trajectory tracking, which makes the spherical underwater vehicles have certain trajectory tracking ability in the vertical plane[3]. Because of the structural symmetry of the underwater vehicles, the coupling degree of horizontal and vertical motion is relatively low, so the spatial motion of the spherical underwater vehicles can be decoupled into horizontal plane[4]. In order to accomplish various tasks underwater, the steering control of the robot is a very important link.

In this paper, aiming at the important problem of the turning ability of the spherical underwater robot, from the point of view of the dynamic control of the robot, a relatively complete dynamic model of the spherical underwater robot is established by comprehensively considering the influence of inertia mass, additional mass, secondary resistance, gravity and buoyancy on the robot[5-7]. On this basis, the steering controller of the spherical underwater vehicle is designed based on the exponential reaching law sliding mode control principle[8-10]. The horizontal steering of the spherical underwater vehicle is controlled to realize the precise steering of the robot. The external disturbance signal is introduced. The steering speed and anti-interference of the robot under the control of the designed controller are tested. The capability lays a foundation for the further research on the space trajectory tracking of spherical underwater vehicles.
2. Controller design

Sliding mode control includes two processes: approaching motion and sliding mode motion. According to the principle of sliding mode variable structure, the reachability condition of sliding mode has no restriction on the specific trajectory of the approaching motion. The dynamic quality of the approaching motion can be improved by using the approach law. Several typical reaching laws include isokinetic reaching law, exponential reaching law, power reaching law and general reaching law. In this paper, exponential reaching law is used to design sliding mode controller.

The expression of exponential reaching law is shown in formula.

\[ s = -c \text{sgn}(s - ks) \quad c > 0, k > 0 \]  

(1)

Where \( s \) is Sliding mode switching function, \( \text{sgn}(.) \) is Sign function, \( \dot{s} = -ks \) is exponential approach term. Its solution is \( s(0)e^{-kt} \).

In exponential approaching, the approaching speed decreases gradually from a larger value to zero, which not only shortens the approaching time, but also makes the velocity of the moving point to the switching surface very small. Simple exponential approximation can not guarantee the arrival of finite time, and there will be no sliding mode on the switching surface, so the constant velocity approximation term \( \dot{s} = -c \text{sgn}s \) should be added.

When \( s \) is close to zero, there is still a certain approaching speed, which can ensure the arrival of finite time. By adjusting parameters \( k \) and \( c \), fast approaching can be guaranteed and chattering can be weakened at the same time.

Assuming that the roll angle \( \phi \) and pitch angle \( \psi \) of the robot are both zero, then

\[ \dot{\theta} = r, \quad \ddot{\theta} = \dot{r} \]  

(2)

According to the whole dynamic model of the robot, the horizontal steering dynamics model of the robot can be obtained as follow.

\[ M = I_z \dot{\theta}(t) + N, \dot{\phi}(t) + N_r(\dot{\phi}(t)) \]  

(3)

Where \( I_z \), \( \dot{\theta}(t) \) is the torque component of the inertia mass term \( M_{\text{in}} \dot{\theta} \) when the robot is turning around Z axis, \( N, \dot{\phi}(t) \) is the torque component of additional mass term \( M_{\text{a}} \dot{\phi} \) when the robot is turning around Z axis, \( N_r(\dot{\phi}(t)) \) is the torque component of the secondary resistance term when the robot is turning around Z axis. The gravity and buoyancy of the robot are in a straight line and the resultant force is zero, so it has no effect on the turning motion of the robot, thus, the controlled object can be expressed as

\[ \dot{\theta}(t) = -f(\theta, t) + bu(t) \]  

(4)

Where

\[ f(\theta, t) = \frac{N_r(\dot{\phi}(t))}{I_z + N_r}, \quad b = \frac{1}{I_z + N_r} \]  

(5)

The input

\[ u(t) = M \]  

(6)

Constructing Sliding Mode Function

\[ s(t) = ce(t) + \dot{e}(t) \]  

(7)

The tracking error and its derivative are as follows

\[ e(t) = \dot{\theta}_d(t) - \dot{\theta}(t), \quad \dot{e}(t) = \ddot{\theta}_d(t) - \ddot{\theta}(t) \]  

(8)

Where \( \dot{\theta}_d(t) \) is the reference yaw angle signal.

Define the Lyapunov function as

\[ V = \frac{1}{2}s^2 \]  

(9)

Then

\[ \dot{s}(t) = c\dot{e}(t) + \ddot{e}(t) = c(\ddot{\theta}_d(t) - \ddot{\theta}(t)) + (\dddot{\theta}_d(t) - \dddot{\theta}(t)) \]
\[
\dot{c}(\dot{\theta}_0(t) - \dot{\theta}(t)) + (\ddot{\theta}_0(t) + f(\theta, t) - bu(t)) = 0
\]

Adopting the law of exponential approach, we have
\[
\dot{s} = -ks - \varepsilon \text{sgn } s, \varepsilon > 0, k > 0
\]
And
\[
\dot{s} = s(-ks - \varepsilon \text{sgn } s) = -ks^2 - \varepsilon ss\text{sgn}(s) = -ks^2 - \varepsilon |s|
\]
Considering \( \varepsilon > 0, k > 0 \), we know \( \dot{s}s < 0 \) and
\[
\dot{V} = s\dot{s} < 0
\]
So the system is asymptotically stable under sliding mode exponential reaching control law.

So the controller of spherical underwater vehicle based on reaching law is as follows:
\[
u(t) = \frac{1}{b} (\varepsilon \text{sgn } s + ks + c(\dot{\theta}_0(t) - \dot{\theta}(t)) + \ddot{\theta}_0(t) + f(\theta, t))
\]

3. Simulation analysis

The control object of this paper is an underactuated spherical underwater robot. The control characteristics of its turning in the horizontal plane are analyzed. According to the above theoretical analysis, this paper uses MATLAB/Simulink software to simulate the system to verify the feasibility and robustness of the sliding mode exponential reaching law controller for the steering control of the robot. The relevant parameters are set as follows:
\[
I_c = 0.3 \text{kgm}^2, N_r = 0.01, c = 2, \varepsilon = 2, k = 5
\]

Figure 1 is the block diagram of steering control system

![Figure 1](image)

Figure 1 The block diagram of steering control system

For the convenience of comparison, the steering performance is simulated without external disturbance and with external sinusoidal disturbance \( d(t) = 0.5 \sin(\pi t) \). Figure 42 and figure 3 are the simulation curves of the steering characteristics of the robot without external disturbance and with external sinusoidal disturbance \( d(t) \), respectively.
4. Results

In this paper, the steering controller of the spherical underwater vehicle is designed based on the sliding mode control principle of exponential approach law, which can control the steering of the horizontal plane of the spherical underwater vehicle. Through the simulation of its control performance, the simulation results are obtained, which verifies the feasibility and effectiveness of the sliding mode control method designed in this paper.
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