Research Article

Active Disturbance Rejection Control of Underwater Vehicle with Omnidirectional Control

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This paper focuses on the omnidirectional drive characteristics and autonomous control of the underwater saucer glider under the condition of underactuated and multiconstraints. Firstly, the dynamic model of the underwater saucer glider is established, and the underactuated control characteristics and the plane biaxial symmetry structure characteristics of the underwater saucer glider are analyzed. An omnidirectional drive mechanism with four water jet thrusters is designed, and the omnidirectional control power output equation is given. Secondly, a nonlinear active disturbance rejection controller is designed, and a visual simulation platform of UUVs based on MATLAB+MFC is established. Through a large number of numerical tests, the reliability and effectiveness of the control strategy are verified, and the smooth operation of the underwater saucer glider in the dynamic process of three-dimensional space is realized.

1. Introduction

With the development of marine science and technology at home and abroad, the use of underwater unmanned vehicles such as underwater gliders and AUVs for marine environment observation and marine resource survey has become a general trend [1, 2]. In terms of dynamic structure and drive mechanism, the underwater glider is quite different from the AUV. AUV generally uses forward or side thrusters for speed adjustment and rudder for course control [3]. But there is no propeller and rudder, the underwater glider can only control the position of gravity’s center through a mass control system inside the platform [4], so as to realize the adjustment of the pitch and roll angles, combined with the underwater glider course adjustments of buoyancy adjustment, the underwater glider heading and attitude control is internal quality control system and the buoyancy adjusting system coupling motion [5], Its essence is to use the metamorphic center moment control method. The core of the metamorphic center moment control method [6] is to adjust the attitude of the vehicle by changing the vehicle center, thus changing the dynamic moment and the position of the gravity center of the body, so as to complete the movement maneuver. With the development of metamorphic center moment control technology, its application field is expanding, and the metamorphic center idea is gradually introduced into the control of the underwater vehicle. The deformed center control of the Graver underwater vehicle at Princeton University has been systematically studied, and a motion model of the underwater vehicle based on Newtonian mechanics has been established. The parameters of the vehicle have been identified through experiments, and the corresponding control system has been designed. The effective control of floating, sinking, and course change has been completed.

In terms of vehicle control strategy research, Hu Kun et al. [7] designed a UUV depth active disturbance rejection controller based on a genetic algorithm according to the characteristics of the operation and control process of unmanned underwater vehicle (UUV) and simulated its depth control under two conditions: no external interference and...
near surface navigation under wave force interference. In literature [8], the control ideas and methods of traditional PID controller and traditional fuzzy controller are introduced, and the control ideas of fuzzy PID control are analyzed, and the gain adjustment fuzzy controller is selected as the motion control method of circular disc glider, and the effectiveness of the algorithm is verified through experiments. This article [9] presents a fault-tolerant tracking control strategy for Takagi–Sugeno fuzzy-model-based nonlinear systems that combines integral sliding mode control with an adaptive control technique. An appropriate fuzzy integral switching surface is designed, and an adaptive fuzzy sliding mode tracking controller is synthesized to ensure the accessibility of the sliding motion despite the effect of actuator faults and unknown disturbances. Yueying Wang [10] instead proposes an integral sliding mode control strategy for a kind of Takagi–Sugeno fuzzy approximation-based nonlinear SPDS under time-varying nonlinear perturbation. An adaptive FISMC is also given to deal with the unknown upper bounds of the matched perturbation. Active disturbance rejection controller (ADRC) has achieved soaring success in nonlinear control systems. Li Sun [11] proposes a quantitative tuning rule for the time-delayed ADRC (TD-ADRC) structure based on the typical first-order plus time delay (FOPTD) model. A sufficient stability condition of TD-ADRC is theoretically derived in terms of active disturbance rejection controller (ADRC) structure based on the typical first-order plus time delay (FOPTD) model. A sufficient stability condition of TD-ADRC is theoretically derived in terms of the scaled parameter pair, the range of which falls within the practical interest. Simulation and experiment validate the tuning efficacy and depict a promising prospective of the proposed method in process control practice.

The underwater saucer glider is also characterized by underactuation but is different from AUV and general underwater gliders in terms of underactuation variables and multiple constraints [12]. From the domestic and foreign glider dynamics and control method research, we aim at the torpedo-shaped structure of underwater unmanned vehicle related research a lot, but the study of disc underwater glider content is less, especially the disc drive characteristics of the glider and omnidirectional characteristics did not give a quantitative analysis. Most of the control algorithms adopted are based on the traditional PID algorithm, and there are few research works on antiocean current interference. The underwater saucer glider studied in this paper adopts the vector-arranged water jet propulsion and the metamaterial center moment structure to adjust its attitude and course, establishes the output drive equation of the saucer glider, analyzes the omnidirectional motion characteristics of the saucer glider from the mathematical mechanism, and gives the stability conditions in the course control process. Aiming at the problem of ocean current interference, a nonlinear active disturbance rejection controller was designed, and a simulation test platform was built to verify the stability of heading control under the condition of ocean current interference.

2. Mathematical Modelling of Disc-Shaped Underwater Glider

For the establishment of the 6DOF kinematics model of the underwater vehicle, two rectangular coordinate systems are adopted in this paper: one is the fixed coordinate system $E - \xi \eta \zeta$, which is fixed to the earth, and the other is the moving coordinate system $G - xyz$. Each coordinate system is defined according to the right-handed system as shown in Figure 1. The $E\xi$ axis is kept horizontal, with the true north as its forward direction in general; the $E\eta$ axis is in the horizontal plane, perpendicular to the axis $E\xi$, with the true east as its forward direction; the $E\zeta$ axis is perpendicular to the $E\xi E\eta$ coordinate plane, and its forward direction points to the earth’s core. The origin of the coordinate system, written as $O$, can be selected at the center of gravity $G$ of the underwater vehicle. In the moving coordinate system $G - xyz$, the $Ox$ axis is generally selected in the central fore-and-aft plane of the underwater vehicle, and its forward direction is pointing to the stern and parallel to the water plane; the $Oy$ axis is perpendicular to the longitudinal section of the underwater vehicle, parallel to the water plane, pointing to the starboard side of the underwater vehicle. The $Oz$ axis is in the central fore-and-aft plane of the underwater vehicle, pointing to the bottom of the underwater vehicle. The position vector and attitude Euler angle $(\phi, \theta, \psi)$ of the underwater vehicle are identified in the fixed coordinate system. The linear velocity $(x, y, z)$ and Euler attitude angle $(\phi, \theta, \psi)$ of the underwater vehicle are identified in the fixed coordinate system. The linear velocity $(u, v, w)$, angular velocity $(p, q, r)$, center-of-gravity position $(x_G, y_G, z_G)$, and longitudinal center on the buoyancy $(x_B, y_B, z_B)$ of the underwater vehicle are identified in the moving coordinate system.

According to Newton’s second law and Euler’s equation, the vector form of the equation of motion of space of the underwater vehicle is obtained as follows:

\[
\begin{align*}
    & m \left[ \frac{\delta V}{\delta t} + \Omega \times V + \frac{\delta \Omega}{\delta t} \times R_G + \Omega \times (\Omega \times R_G) \right] = F_S, \\
    & I \left[ \frac{\delta \Omega}{\delta t} + \Omega \times (\Omega \times R_G) + R_G \times \frac{\delta V}{\delta t} + \Omega \times (R_G \times mV) \right] = T_S. 
\end{align*}
\]

(1)

In general, the external shape of the underwater vehicle is symmetrical in left and right, up and down, and front and back, and the rotational inertia of the underwater vehicle can be obtained as follows:

**Full symmetry in front and back is expressed as follows:**

\[
I_{zx} = I_{xz} = I_{xy} = I_{yx} = 0. 
\]

(2)

**Full symmetry in left and right is expressed as follows:**

I_{xy} = I_{yx} = I_{yz} = I_{zy} = 0. \quad (3)

Full symmetry in up and down is expressed as follows:

\[ I_{yz} = I_{zy} = I_{xz} = I_{zx} = 0. \quad (4) \]

When the center of gravity \( G \) of the disc-shaped underwater vehicle does not coincide with the origin \( O \) of the moving system, the 6DOF kinematics equation of the disc-shaped underwater vehicle is obtained as follows:

\[
\begin{aligned}
\mathbf{I}_x \ddot{\phi} + (I_z - I_y) \dot{q} r + m \left[ y_G (\dot{w} + pv - qu) - z_G (\dot{v} + ru - pw) \right] &= K, \\
\mathbf{I}_y \ddot{q} + (I_x - I_z) \dot{r} p + m \left[ z_G (\dot{u} + qw - rv) - x_G (\dot{v} + ru - pw) \right] &= M, \\
\mathbf{I}_z \ddot{r} + (I_y - I_x) \dot{p} q + m \left[ x_G (\dot{v} + ru - pw) - y_G (\dot{u} + qw - rv) \right] &= N.
\end{aligned}
\]

As the underwater vehicle moves on water level \( xoy \), \( \omega = p = q = \dot{w} = \dot{p} = \dot{q} = 0 \), and variable \((u, v, r)\), the equation is simplified as follows:

\[
\begin{aligned}
\mathbf{I}_x \ddot{\phi} + (I_z - I_y) \dot{q} r + m \left[ y_G (\dot{w} + pv - qu) - z_G (\dot{v} + ru - pw) \right] &= X, \\
\mathbf{I}_y \ddot{q} + (I_x - I_z) \dot{r} p + m \left[ z_G (\dot{u} + qw - rv) - x_G (\dot{v} + ru - pw) \right] &= Y, \\
\mathbf{I}_z \ddot{r} + (I_y - I_x) \dot{p} q + m \left[ x_G (\dot{v} + ru - pw) - y_G (\dot{u} + qw - rv) \right] &= N.
\end{aligned}
\]

The equation can be further simplified as follows:

\[
\begin{aligned}
\mathbf{I}_x \ddot{\phi} + (I_z - I_y) \dot{q} r + m \left[ y_G (\dot{w} + pv - qu) - z_G (\dot{v} + ru - pw) \right] &= X, \\
\mathbf{I}_y \ddot{q} + (I_x - I_z) \dot{r} p + m \left[ z_G (\dot{u} + qw - rv) - x_G (\dot{v} + ru - pw) \right] &= Y, \\
\mathbf{I}_z \ddot{r} + (I_y - I_x) \dot{p} q + m \left[ x_G (\dot{v} + ru - pw) - y_G (\dot{u} + qw - rv) \right] &= N.
\end{aligned}
\]
\[
\begin{align*}
\mathbf{m}(\ddot{u} - vr - x_G r^2 - y_G r^2, \ddot{v} + ur - y_G r^2 + x_G r^2) &= X, \\
I_\tau \dot{r} + m[x_G (\dot{v} + ru) - y_G (\dot{u} - rv)] &= N.
\end{align*}
\]

As the underwater vehicle moves in the horizontal section of the vehicle, \(xoz\), \(v = p = r = \dot{v} = \dot{p} = \dot{r} = 0\), and variable \((u, w, q)\), the equation is simplified as follows:

\[
\begin{align*}
\mathbf{m}[\dot{u} + wq - x_G q^2 + z_G \dot{q}] &= X, \\
\mathbf{m}[\dot{w} - uq + vp - z_G p^2 - x_G \dot{p}] &= Z, \\
I_y \dot{q} + m[z_G (\dot{u} + qw - rv) - x_G (\dot{w} - qu)] &= M.
\end{align*}
\]

As the underwater vehicle moves in the rolling surface \(yoz\), \(u = q = r = \dot{u} = \dot{q} = \dot{r} = 0\), and variable \((v, w, p)\), the equation is simplified as follows:

\[
\begin{align*}
\mathbf{m}[\dot{v} - wp + ur - y_G (r^2 + p^2) + z_G (qr - \dot{p}) + x_G (qp - \dot{r})] &= Y, \\
\mathbf{m}[\dot{w} - uq + vp - z_G (p^2 + q^2) + x_G (rp - \dot{q}) + y_G (rq + \dot{p})] &= Z, \\
I_x \dot{p} + (I_x - I_y) qr + m[y_G (\dot{w} + pv - qu) - z_G (\dot{v} + ru - pw)] &= K.
\end{align*}
\]

The above equations are the general 6DOF kinematics equations for unmanned underwater vehicles. If it is assumed that \(G, O\) points coincide, that is, \(x_G = y_G = z_G = 0\), the above equation can be further simplified.

### 3. Analysis of Output Dynamic Characteristics

The disk-shaped vehicle adopts the mixed control structure of metamorphic center moment and vector propulsion to adjust the attitude and motion control of the vehicle [13]. Through the vector synthesis between the nozzles, the forward and backward motion, left-right translation, and self-rotation of the vehicle can be controlled. The saucer vehicle is placed inside the vehicle by four water injection pumps, and the nozzle is arranged at the edge of the saucer vehicle. Four circular nozzles were designed for this underwater saucer vehicle, respectively, T1, T2, T3, and T4. The specific positions of the four nozzles are shown in Figure 2 (horizontal section). The angles between the center of the four nozzles and the axis are \(-45^\circ\), \(+45^\circ\), \(135^\circ\), and \(-135^\circ\), respectively, and the spray directions of the nozzles are shown in the arrows.

Therefore, according to the distribution of the water jet pumps, we can conclude that in the vehicle-body coordinate system, the thrust of the water jet propeller to the center of mass is (vector form) as follows:

\[
F = \frac{\sqrt{2}}{2} [F_1 + F_2 - F_3 - F_4, F_1 - F_2 - F_3 + F_4, 0]^T.
\]

Torque generated by thrust of the jet propeller is as follows:

\[
M = [0\ 0\ (F_2 + F_4 - F_1 - F_3) R]^T,
\]

where \(R\) axis is the distance from the thrust line to the center of mass.

Assume the resultant vector of \(F_1\) and \(F_3\) is \(F_{13}\), the resultant vector of \(F_2\) and \(F_4\) is \(F_{24}\), the resultant vector of \(F_1\), \(F_2\), \(F_3\), and \(F_4\) is \(F_z\), and the resultant moment of the disc-shaped vehicle is \(M\). The scalar form of torque and resultant force can be deduced as follows:
The characteristics of the underwater saucer glider can be obtained as follows:

\[ F_{1,3} = F_1 - F_3 = F_x \cos(a - 45^\circ), \]
\[ F_{2,4} = F_2 - F_4 = F_x \sin(a - 45^\circ), \]
\[ M = \frac{d}{2} \left( F_1 - F_3 + F_2 - F_4 \right), \]
\[ F_1, F_2, F_3, F_4 \geq 0. \]

The relationship between \( F_1, F_2, F_3, \) and \( F_4 \) can be expressed as follows:

\[
\begin{cases}
F_1 = F_1, \\
F_2 = F_1 - \frac{M}{d} \cdot \frac{\sqrt{2}}{2} F_x \cos(a), \\
F_3 = F_1 - F_x \cos\left(a - \frac{\pi}{4}\right), \\
F_4 = F_1 - \frac{M}{d} \cdot \frac{\sqrt{2}}{2} F_x \cos(a - \frac{\pi}{4}).
\end{cases}
\tag{15}
\]

According to the driving equation of the underwater saucer glider, the heading angle \( \alpha \) of the vehicle can be adjusted by changing the output force of the four water jets, \( T_1, T_2, T_3, \) and \( T_4 \), and the 360° in situ turning motion characteristic of the saucer glider can be realized. According to equation (15), assuming that the output vector torque of \( T_1, T_2, T_3, \) and \( T_4 \) is the same, the omnidirectional characteristics of the underwater saucer glider can be obtained as follows:

1. Turn on \( T_3 \) and \( T_4 \), and turn off \( T_1 \) and \( T_2 \) at the same time. The disc glider can realize the translation movement along the positive \( y \)-axis, and the translation movement along the negative \( y \)-axis can be obtained in the same way.
2. Turn on \( T_2 \) and \( T_3 \), and turn off \( T_1 \) and \( T_4 \) at the same time. The disc glider can realize clockwise rotation motion, and in the same way, the counterclockwise rotation motion attitude can be controlled.
3. Turn on \( T_1 \) and \( T_3 \), and turn off \( T_2 \) and \( T_4 \) at the same time. The disc glider can realize the translation movement along the negative \( y \)-axis, and the translation movement along the positive \( y \)-axis can be obtained in the same way.

4. Set the heading \( \alpha \) by equation (15) to get the output of the four water jets of the saucer glider. Changing the output of the four water jets can make the saucer glider adjust to the set heading, and the setting range is 0°–360°.

4. Analysis of Stability of Closed-Loop Course Control System

Underwater gliders have no propeller and rudder in general, resulting in the steering of underwater glides completely different from self-powered underwater vehicles such as AUV and ROV. In terms of the theory of course control, underwater gliders are also quite different from other underwater vehicles [14]. For the study of AUV course control, it is feasible to only consider the \( xoy \) law of motion on the horizontal plane. However, for the study of the course control of underwater gliders, only the oil bag buoyancy, roll mass block torque and pitch mass block torque in the vertical direction can be adjusted; the pitch angle of underwater gliders is changed by adjusting the size of the whole pitching mass block matrix; the vertical buoyancy of the underwater gliders can be changed by adjusting the amount of oil in the external oil bag. Only 3 driving forces can be generated by underwater gliders directly: buoyancy, roll torque, and pitch moment. The position of the center of gravity is controlled by the mass block adjustment system inside the platform, realizing the pitch and roll angle adjustment, as well as course control of underwater gliders combined with buoyancy adjustment. Therefore, the course control of underwater gliders is a rotating motion generated by the coupling action of the internal mass control system and the buoyancy control system, and the horizontal displacement, vertical displacement, yaw moment, and other variables are the result of the coupling action of the kinematic system.

According to the law of course control of underwater gliders, it can be seen that: \( X = Y = N = 0, Z \neq 0, K \neq 0, M \neq 0 \).

The mathematical description of underwater glider course control is as follows:

\[
m[u - vr + wq] = 0, \tag{16a}
\]
\[
m[\dot{v} - wp + ur] = 0, \tag{16b}
\]
\[
m[\dot{w} - uq + vp] = Z, \tag{16c}
\]
\[
I_x \ddot{p} + (I_z - I_y) qr = K, \tag{16d}
\]
\[I_y \ddot{q} + (I_x - I_z) r p = M, \quad (16e)\]
\[I_z \dot{r} + (I_y - I_x) p q = 0. \quad (16f)\]

To calculate yaw angular acceleration, take the derivation of both sides of equation (16f) as follows:
\[I_z \ddot{r} + (I_y - I_x) \left( p \dot{q} + p \ddot{q} \right) = 0. \quad (17)\]

From equations (16d) and (16e), \( \dot{p} = 1/I_x [K - (I_z - I_x) qr] \) and \( \dot{q} = 1/I_y [M - (I_x - I_z) rp] \), the following can be obtained:
\[I_z \ddot{r} + (I_y - I_x) \frac{d}{dx} \left[ K - (I_z - I_x) qr \right] \]
\[- (I_y - I_x) \frac{d}{dy} \left[ M - (I_x - I_z) rp \right] = 0. \quad (18)\]

Because underwater vehicles have no active steering mechanism such as a steering rudder, the passive course control can only be realized by adjusting pitch angle and rolling angle. The course control system obtains the displacement of the longitudinal and transverse mass blocks of the vehicle according to the real-time estimation of course and the calculation of course. The pitch and roll angles are obtained by the weight component generated by the mass blocks. The control link has a serious time lag problem. Therefore, the time lag greatly affects the stability of the whole course control system. The course control with time lag system adopts state feedback control law, \( K = k_p \psi + k_d \dot{\psi} + k_a \ddot{\psi} \), where \( M = 0 \), \( \psi_f = \psi(t - \tau), \dot{\psi}_f = \dot{\psi}(t - \tau), \) \( \dot{\psi}_f = \dot{\psi}(t - \tau), r(t) = \psi(t), \) and \( \psi \) is the bow-direction angle. By substituting this relation into the mathematical model (17), the dynamic equation of course control of underwater glider can be obtained as follows:
\[I_z \dot{\psi}(t) + (I_y - I_x) \frac{k_a}{I_x} \dot{\psi}(t - \tau) + (I_y - I_x) \frac{k_d}{I_x} \ddot{\psi}(t - \tau) + \left( I_y - I_x \right) \frac{q^2}{I_x} \frac{d}{dx} \left[ K - (I_x - I_z) qr \right] \]
\[+ \frac{\dot{I}_y}{I_y} \left( I_y - I_x \right) \frac{p^2}{I_z} \right] \psi(t) = 0. \quad (19)\]

Rewrite the above equation to
\[\dot{\psi}(t) + s_1 \dot{\psi}(t - \tau) + s_2 \ddot{\psi}(t - \tau) + s_3 \dot{\psi}(t - \tau) + \eta \dot{\psi}(t) = 0, \quad (20)\]

where
\[\eta = (I_x - I_y)(I_x - I_z) \frac{q^2}{I_x I_z} + (I_y - I_x)(I_x - I_z) \frac{p^2}{I_y I_z}, \]
\[s_1 = (I_y - I_x) \frac{k_a}{I_x} q, \]
\[s_2 = (I_y - I_x) \frac{k_d}{I_x} q, \]
\[s_3 = (I_y - I_x) \frac{k_a}{I_x} q. \quad (21)\]

On the basis of equation (20), without considering the time lag factor, the time-lag-free disturbance equation of bow-direction angle \( \psi \) under control condition is as follows:
\[\dot{\psi}(t) + s_1 \dot{\psi}(t) + (s_2 + \eta) \ddot{\psi}(t) + s_3 \dot{\psi}(t) = 0. \quad (22)\]

When the vehicle is disturbed, the bow-direction angle has an increment \( \Delta \psi \) and substitute the amount of disturbance \( \Delta \delta \), into equation (22),
\[\lambda^3 + s_1 \lambda^2 + (s_2 + \eta) \lambda + s_3 = 0. \quad (25)\]

To make the vehicle has directional control stability in the horizontal plane, according to the Hurwitz discriminant method [15], the underwater vehicle has the stability
conditions under the condition of direction control has no
time lag impact:
\[
\begin{align*}
  s_1 & > 0, \\
  s_2 + \eta & > 0, \\
  s_1(s_2 + \eta) & > s_3.
\end{align*}
\]

(26)

5. Design of Active Disturbance
Rejection Controller

In the control process of the disc-shaped underwater glider,
the ADRC algorithm is used for the course control to resist

6. Numerical Calculation and
Simulation Verification

The physical parameters of the disc-shaped underwater
glider platform used in the numerical simulation are shown in Table 1.

Based on the mathematical model of the underwater disc
glider, a visual simulation platform of the unmanned under-
water vehicle based on MATLAB+MFC has been established (Figure 3). This platform can realize the calculation and simulation of the control algorithm of the disc-shaped underwater glider, the display and drawing of control state data, and the 3D dynamic process of the disc-shaped underwater glider, providing a good platform for the re-
search of motion control strategy and the development of
the autonomous control system. Figure 4 is the data of pitch
motion characteristics of an underwater saucer glider, and
Figure 5 is the data of V-shaped motion characteristics of an
underwater saucer glider. Yaw angle \( \psi \) channel parameter setting is as follows:

\[
\begin{align*}
  \beta_{01} & = 200, \\
  \beta_{02} & = 300, \\
  \beta_{03} & = 500, \\
  r & = 32, \\
  h_0 & = 0.02.
\end{align*}
\]

(30)

6.1. Anticurrent Interference Control Experiment. The angle
between the direction of sea current and the x-axis was set at
20°, and the sea current’s size was 1 kn. The ”V” shape path
was adopted for the depth profile of the underwater saucer
glider. On the visual simulation platform (Figure 3), after
setting the glider’s structural parameters, environmental

\[
\begin{align*}
  e_y(k) & = z_1(k) - \psi_1(k), \\
  e_\psi(k) & = \psi_{d1}(k) - \psi_d(k), \\
  u_{\psi 0}(k) & = \text{fhan}(e_{\psi 1}, e_{\psi 2}, r, h_0), \\
  u_{\psi}(k) & = u_{\psi 0}(k) \left( \frac{z_3(k)}{b_0} \right).
\end{align*}
\]

(27)

(28)

(29)
parameters, control parameters, and simulation parameters, the numerical calculation results obtained from the simulation operation are shown in Figures 4 and 5.

According to the simulation results in Figures 4 and 5, it can be seen that the underwater saucer glider runs stably along with the set “V” shape path on the depth profile. In the process of operation, it is disturbed by the 1 kn sea current, and there are slight fluctuations in the roll direction and yaw direction, but the numerical magnitude is very small. It is verified that the nonlinear anti-interference controller can keep the control stability under the sea current disturbance in a certain range.

6.2. Coupling Influences Control the Experimental Process. When the pitch angle of the glider is set to 20°, sinusoidal interference is applied to the roll direction with an amplitude of ±5°. Using the traditional PID control algorithm designed in this paper, the following results are obtained through numerical calculation. It can be seen from Figure 7 that, in the step response, the steady-state running time of the control algorithm designed in the paper is 0.2 s, and the response is quick and fully meets the dynamic adjustment process of the underwater glider.

| Variable                  | Signal | Initial value | Unit |
|----------------------------|--------|---------------|------|
| Total mass                 | m      | 112.69        | kg   |
| Maximum buoyancy           | T      | 0.113         | m³   |
| Itsself buoyancy           | B₀     | 676.2         | N    |
| Gravitational acceleration | g      | 9.81          | m/s² |
| Roll mass                  | m₁     | 0.5           | kg   |
| Pitch mass                 | m₂     | 0.5           | kg   |
| Velocity                   | (u, v, w) | (0, 0, 0) | m/s  |
| Angular velocity           | (p, q, r) | (0, 0, 0) | rad/s|
| Attitude angle             | (φ, θ, ψ) | (0, 0, 0) | rad  |
| Center-of-gravity position | (xGI, yGI, zGI) | (0, 0, 0.005) | m   |
| Buoyancy position          | (xB, yB, zB) | (0, 0, 0) | m   |
| Limit of 1st slider        | (x₁, y₁, z₁) | (0, -0.02, 0) | m  |
| Limit of 2nd slider        | (x₂, y₂, z₂) | (0, 0.02, 0) | m  |

Figure 3: Visual simulation platform for motion control of the underwater disc glider.

Figure 4: Visual simulation platform for motion control of the underwater disc glider.

$k_d = 20$. Figure 6 was obtained through numerical calculation. It can be found that the pitch angle of the saucer glider is controlled around 20°, and within the range of up and down fluctuation of 2°, the pitch angle has obvious periodic fluctuation. It can be seen that the traditional PID control algorithm cannot solve the coupling effect of roll motion and pitch motion of the underwater dish glider.

When the pitch angle of the glider is set to 20°, sinusoidal interference is applied to the roll direction with an amplitude of ±5°. Using the nonlinear active disturbance rejection algorithm designed in this paper, the following results are obtained through numerical calculation. According to the results, it can be found that the pitch angle of the saucer glider is controlled in the vicinity of 20° and within the range of fluctuation of 0.5°, which reaches the control expectation. It can also be seen from Figure 7 that, in the step response, the steady-state running time of the control algorithm designed in the paper is 0.2 s, and the response is quick and fully meets the dynamic adjustment process of the underwater glider.
Figure 4: Antijamming control data of pitch motion of the underwater saucer glider.

Figure 5: V-shaped motion data of underwater saucer glider.
underwater saucer glider. The method can also be used to analyze the influence of yaw direction disturbance on pitch angle control.

7. Conclusions

This paper focuses on the autonomous control of the disc-shaped underwater vehicle under the condition of underactuation and multiple constraints. The plane biaxial symmetry structure of the disc-shaped underwater vehicle is analyzed, and the motion modes of each section are simplified. According to the analysis of nonlinear control stability, the global asymptotic stability condition of the system is given; an active disturbance rejection controller suitable for the disc-shaped vehicle is designed, which enables the vehicle with omnidirectional motion characteristics and highly flexible maneuverability, as well as reliable stability and strong robustness. Finally, the visual simulation platform of the unmanned underwater vehicle based on MATLAB + MFC is established. This platform can realize the calculation and simulation of the control algorithm of the disc-shaped underwater glider, providing a good platform for the research of motion control strategy and the development of autonomous control system. According to the control state data of a large number of numerical experiments, the ADRC designed in this paper can realize the smooth operation of the 3D dynamic process of the disc-shaped underwater glider, verified the effectiveness of the control strategy.

This paper focuses on the autonomous control of the underwater saucer vehicle under the condition of underactuation and multiple constraints. This paper analyzes the characteristics of the plane biaxial symmetry drive structure of the underwater saucer vehicle, establishes the output drive equation of the saucer glider, and analyzes the omnidirectional motion characteristics of the saucer glider from the mathematical mechanism. According to the nonlinear control stability analysis, the global asymptotic stability condition of the system is given, and the active disturbance rejection controller suitable for the saucer structure vehicle is designed. Through numerical calculation experiments, it is verified that the system has reliable stability and strong robustness under the condition of ocean current disturbance and channel coupling. Finally, a visual simulation platform
for UUVs based on MATLAB+MFC is established. This platform can realize the simulation of the control algorithm of the underwater saucer glider and is good for the research of motion control strategy and the development of the autonomous control system. From the control state data of a large number of numerical tests, it can be seen that the ADRC designed in this paper can realize the smooth operation of the 3D dynamic process of the underwater saucer glider, and the effectiveness of the control strategy is verified. Through the research on the omnidirectional driving characteristics and the ADRC algorithm of the underwater saucer glider, the theoretical research of the underwater saucer glider can be promoted to the engineering application. In particular, the omnidirectional driving feature makes the underwater saucer glider free of turning radius limitation, movement flexibility, and control stability. It can be predicted that the underwater saucer glider will have obvious application prospects in port reconnaissance and operation on complex terrain in narrow sea areas.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Wen-Qing Zhang carried out project demonstration, theoretical derivation, and systematic design; Liang-Long Da contributed to conceptualization; Wu-Hong Guo reviewed and edited the manuscript; Yong Lv was responsible for software; Mei Han supervised the study. All authors have read and agreed to the final version of the manuscript.

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