Research Article

The Bioinspired Model-Based Hybrid Sliding-Mode Formation Control for Underactuated Unmanned Surface Vehicles

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In this paper, a novel hybrid strategy is proposed for unmanned surface vehicle (USV) formation control. The strategy is divided into two subsystems: a virtual velocity controller based on the bioinspired model and a dynamic controller based on the sliding-mode model. The proposed control scheme solves the problem of a speed jump that occurs in the traditional backstepping method when the margin of error increases suddenly, and it also satisfies the actuator control constraint. Additionally, a dynamic controller is designed, combining the sliding mode with the proposed virtual controller, to avoid the traditional chattering problem. System stability is proven by the Lyapunov theory. Simulation results verify the effectiveness of the proposed controller.

1. Introduction

The formation control of USVs is receiving increasing interest in control science and engineering [1–3]. Multiple USVs can accomplish challenging and dangerous tasks, such as mine clearance, patrol, investigation, and the transportation of strategic materials, which can not only decrease personal injury but also achieve tasks that a single USV cannot complete [4]. To achieve a desirable formation pattern, several methods including leader-follower approach [5], virtual structure strategy [6], behavioral-based approach [7], and artificial potential function [8] have been proposed. Among these methods, the leader-follower strategy is commonly used because of simplicity and scalability. To address the formation problem, many control schemes have been implemented. An adaptive backstepping method for a group of underactuated autonomous vehicles was studied in [9, 10], and the course angle error between leader and follower was considered to guarantee the follower's course angle stability. A Linear Quadratic Regulator Proportional Integral (LQR PI) controller was implemented in [11] for centralized heterogeneous leader-follower architecture. With this control scheme, formation geometry can be switched to any shape while flying, and obstacle avoidance can be realized. In [12], a sliding-mode control law for controlling multiple

USVs in arbitrary formations was proposed, mesh stability and parameter uncertainty in the dynamic model and wave disturbance were considered in designing the controllers, and the effectiveness of the controller was verified by the computer simulation. Though it has an outstanding characteristic insensitivity to parameter variations, one major drawback of sliding-mode control is the inherent problem of chattering. In addition, many intelligent methods were used to achieve formation control. A bounded neural network control law was constructed with the aid of a saturated function for the USV while over a closed curve in [13]. An adaptive neural network formation controller combined with a dynamic surface technique for USVs was studied in [14], which solved the problem of “explosion of complexity” by introducing the first-order filter. In [15], a robust adaptive formation control law is proposed for multiple autonomous surface vehicles moving in a leader-follower formation. However, while all works mentioned above have common styles, the procedure for designing a controller is complex, and too many parameters needed to be adjusted. Based on graph-theoretic concepts and locally distributed information, a neural fuzzy formation controller was designed with the capability of online learning in [16]. Mu and Wang [17] proposed fuzzy-based path following control for USV to solve the problem of unknown control gain coefficient. The fuzzy rules-based

formation control approaches can solve the problem of large initial robot velocities, but formulating the fuzzy rules is not easy because they are usually obtained by trial and error based human knowledge [18]. A neural network needs either online learning or offline training procedures, either of which could be computationally complicated.

The main contribution of this work is to solve the problem of the speed jump and actuator control constraints of USV formation. The leader-follower strategy is used since it is easy to implement. When the controller is designed, a virtual USV is introduced to produce a predefined path, and the other USV keeps the desired distance and angle with it to achieve the desired formation pattern. A bioinspired model-based hybrid sliding-mode controller is designed, inspired by [19], and on the basis of the previous literature [4]. It can not only avoid the traditional chattering problem and smooth the input signal but also simplify the control law.

2. Formation Model of USV

2.1. Single USV Model. Consider a class of networked multi-agent systems consisting of n -unmanned surface underactuated vehicles. The dynamical model of the i -th USV is given by [20]

$$\begin{aligned}\dot{x}_i &= u_i \cos \psi_i - v_i \sin \psi_i \\ \dot{y}_i &= u_i \sin \psi_i + v_i \cos \psi_i \\ \dot{\psi}_i &= r_i \\ \dot{u}_i &= \frac{m_{22i}}{m_{11i}} v_i r_i - \frac{d_{11i}}{m_{11i}} u_i + \frac{1}{m_{11i}} \tau_{ui} + \frac{d_u}{m_{11i}} \\ \dot{v}_i &= -\frac{m_{11i}}{m_{22i}} u_i r_i - \frac{d_{22i}}{m_{22i}} v_i + \frac{d_v}{m_{22i}} \\ \dot{r}_i &= \frac{m_{11i} - m_{22i}}{m_{33i}} u_i v_i - \frac{d_{33i}}{m_{33i}} r_i + \frac{1}{m_{33i}} \tau_{ri} + \frac{d_r}{m_{33i}}\end{aligned}\quad (1)$$

The signals x_i , y_i , and ψ_i denote position and orientation (yaw angle), respectively, in the earth fixed frame. u_i , v_i , and r_i represent the surge, sway, and yaw velocities with respect to body frame, respectively. m_{ii} denotes the masses including added masses in the surge, sway and yaw axes. The damping term in the body coordinate is described by d_{ii} . The signals $\tau = (\tau_{ui}, 0, \tau_{ri})^T$ are the surge force and yaw torque inputs provided by thrusters. $W = [d_u, d_v, d_r]^T$ denotes the loads induced by waves, wind, and ocean currents along the surge, sway, and yaw axes, respectively [21].

2.2. USV Formation Model. In this work, the formation control problem for USV is addressed by a distributed strategy based on virtual leader strategy. For convenience, only 2 USVs are considered as a group. The mathematical model is formed as in Figure 1: where l is the distance between leader USV and follower USV, φ is described as the relative angle between follower and leader, l_d , φ_d are the desired distance and angle, and l_x , l_y represent the components of l in the earth fixed frame on x - and y -axes. p is the bow position

FIGURE 1: Leader-follower formation configuration with the control point P.

of USV, x_{FP} , y_{FP} , ψ_{FP} are the position and orientation of p , and d is the distance between p and the mass center of the follower. We can construe from Figure 1 that

$$\begin{aligned}x_{FP} &= x_F + d \cos \psi_F, \\ y_{FP} &= y_F + d \sin \psi_F\end{aligned}\quad (2)$$

To achieve the desired formation pattern, the following inequality should be guaranteed:

$$\begin{aligned}\lim_{t \rightarrow \infty} l - l_d &\leq \zeta_1, \\ \lim_{t \rightarrow \infty} \varphi - \varphi_d &\leq \zeta_2\end{aligned}\quad (3)$$

ζ_1 , ζ_2 are positive constants that can be arbitrarily small. l_d , φ_d are the desired distance and angle yet bounded and there exist a positive constant, that is, ρ_1 , ρ_2 , such that $\|\dot{l}_d\| \leq \rho_1$, $\|\dot{\varphi}_d\| \leq \rho_2$.

If the value of l , φ can be confirmed, then the value of l_x , l_y can be confirmed, and then the value of l , φ can be transformed to control l_x , l_y . As seen from the picture,

$$\begin{aligned}l_x &= l \cos \theta = x_L - x_F - d \cos \psi_F, \\ l_y &= l \sin \theta = y_L - y_F - d \sin \psi_F\end{aligned}\quad (4)$$

Then,

$$\begin{aligned}\dot{l}_x &= u_L \cos \psi_L - v_L \sin \psi_L - (u_F \cos \psi_F - v_F \sin \psi_F) \\ &\quad + dr_F \sin \psi_F \\ \dot{l}_y &= u_L \sin \psi_L + v_L \cos \psi_L - (u_F \sin \psi_F + v_F \cos \psi_F) \\ &\quad - dr_F \cos \psi_F\end{aligned}\quad (5)$$

The desired distance between 2 USVs is considered as l_d , and the projection weight in the earth fixed frame is l_x^d , l_y^d , so

$$\begin{aligned}l_x^d &= -l_d \cos (\varphi_d + \psi_L), \\ l_y^d &= -l_d \sin (\varphi_d + \psi_L)\end{aligned}\quad (6)$$

Differentiating (6) yields

$$\begin{aligned}\dot{l}_x^d &= -\dot{l}_d \cos(\varphi_d + \psi_L) + l_d \dot{\varphi}_d \sin(\varphi_d + \psi_L) \\ &\quad + l_d r_L \sin(\varphi_d + \psi_L) \\ \dot{l}_y^d &= -\dot{l}_d \sin(\varphi_d + \psi_L) + l_d \dot{\varphi}_d \cos(\varphi_d + \psi_L) \\ &\quad + l_d r_L \cos(\varphi_d + \psi_L)\end{aligned}\quad (7)$$

The errors of the formation model can be defined as

$$\begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix} = \begin{bmatrix} \cos \psi_F & \sin \psi_F & 0 \\ -\sin \psi_F & \cos \psi_F & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} l_x - l_x^d \\ l_y - l_y^d \\ \psi_L - \psi_F \end{bmatrix}\quad (8)$$

From what has been discussed above, the formation mathematics model can be written as follows:

$$\begin{aligned}\dot{e}_x &= e_y r_F - u_F + u_L \cos e_\psi - v_L \sin e_\psi \\ &\quad - l_d r_L \sin(\varphi_d + e_\psi) + \mu_1 \\ \dot{e}_y &= -e_x r_F - v_F + u_L \sin e_\psi - v_L \cos e_\psi - dr_F \\ &\quad + l_d r_L \cos(\varphi_d + e_\psi) + \mu_2 \\ \dot{e}_\psi &= r_L - r_F \\ \dot{u}_F &= \frac{m_{22}}{m_{11}} v_F r_F - \frac{d_{11}}{m_{11}} u_F + \frac{1}{m_{11}} \tau_{uF} + \frac{d_u}{m_{11}} \\ \dot{v}_F &= -\frac{m_{11}}{m_{22}} u_F r_F - \frac{d_{22}}{m_{22}} v_F + \frac{d_v}{m_{22}} \\ \dot{r}_F &= \frac{m_{11} - m_{22}}{m_{33}} u_F v_F - \frac{d_{33}}{m_{33}} r_F + \frac{1}{m_{33}} \tau_{rF} + \frac{d_r}{m_{33}}\end{aligned}\quad (9)$$

where

$$\begin{aligned}\mu_1 &= \dot{l}_d \cos(\varphi_d + e_\psi) - l_d \dot{\varphi}_d \sin(\varphi_d + e_\psi), \\ \mu_2 &= \dot{l}_d \sin(\varphi_d + e_\psi) + l_d \dot{\varphi}_d \cos(\varphi_d + e_\psi),\end{aligned}\quad (10)$$

and we can get that μ_1, μ_2 are bounded since $|\sin(\varphi_d + e_\psi)| \leq 1$, $|\cos(\varphi_d + e_\psi)| \leq 1$, l_d, φ_d are bounded, and $\|\dot{l}_d\| \leq \rho_1$, $\|\dot{\varphi}_d\| \leq \rho_2$.

Based on [4], we have the following assumptions.

Assumption 1. The surge velocity $u_i \geq 0$.

Assumption 2. Trajectory (x_l, y_l) produced by the virtual leader satisfies that its derivatives with respect to t exit up to second order.

Assumption 3. The terms d_u, d_v, d_r that satisfy $d_u \leq |D_u|, d_v \leq |D_v|, d_r \leq |D_r|, D_u, D_v, D_r$ are constants.

Assumption 4. The follower can receive the position and velocity information from the leader by sensors in time.

In summary, the underactuated USV formation control problem can be divided into two parts: kinematics control and dynamics control.

For kinematics control, virtual surge, and sway velocities are designed to make

$$\begin{aligned}\lim_{t \rightarrow \infty} l_x &\rightarrow l_x^d, \\ \lim_{t \rightarrow \infty} l_y &\rightarrow l_y^d\end{aligned}\quad (11)$$

For dynamics control, surge force and yaw torque are designed to make actual velocities approximate to virtual velocities.

3. Hybrid Control Strategy for Unmanned Surface Vehicles

3.1. Virtual Velocity Controller. The virtual velocity controller based on the backstepping approach can be defined as

$$\begin{bmatrix} u_d \\ v_d \\ r_d \end{bmatrix} = \begin{bmatrix} k_1 e_x + u_L \cos e_\psi - v_L \sin e_\psi + e_y r_F - l_d r_L \sin(\varphi_d + e_\psi) + \mu_1 \\ k_2 e_y - e_x r_F + u_L \sin e_\psi - v_L \cos e_\psi - dr_F + l_d r_L \cos(\varphi_d + e_\psi) + \mu_2 \\ r_L + k_3 e_\psi \end{bmatrix}\quad (12)$$

Here, u_d, v_d, r_d are the virtual surge, sway, and yaw motion speed of the following USVs, u_L, v_L, r_L are the desired velocity in the body-fixed frame, and k_1, k_2, k_3 are a positive constant, respectively.

3.2. Bioinspired Velocity Controller. With the analysis of (12), the virtual speed is directly related to the state error. The traditional backstepping method will generate a sharp speed

jump when a sudden tracking error occurs. This means that large acceleration and forces/moments are required that make exceeding the control constraint practically impossible. To solve the speed jump and control constraint problems, a bioinspired model is introduced to design the virtual speed controller.

The bioinspired neural dynamics model was first put forward by Grossberg [21]. It can describe the online adaptive behavior of individuals. It was originally derived based on the

membrane model proposed by Hodgkin and Huxley [22] for a patch of membrane using electrical elements. The dynamics of voltage across the membrane can be described in the membrane model, using state equation technique as

$$C_m \frac{dV_m}{dt} = -(E_p + V_m) g_p + (E_{Na} - V_m) g_{Na} - (E_k + V_m) g_k \quad (13)$$

where V_m is the neural activity of the j -th neuron in the neural network, the parameters $E_p + V_m$, $E_{Na} - V_m$, $E_k + V_m$ are nonnegative constants representing the passive decay rate, the upper and lower bounds of the neural activity, respectively, and the variables the excitatory and inhibitory inputs to the neuron.

The bioinspired model can be defined as following form:

$$\dot{V}_i = -AV_i + (B - V_i) f(e_i) - (D + V_i) g(e_i) \quad (14)$$

where

$$f(e_i) = \begin{cases} e_i, & e_i \geq 0 \\ 0, & e_i < 0, \end{cases} \quad (15)$$

$$g(e_i) = \begin{cases} -e_i, & e_i \leq 0 \\ 0, & e_i > 0. \end{cases}$$

In this work, the tracking errors e_x , e_y , e_ψ are chosen as the input of the neural dynamic model, and the outputs V_i will substitute the error of e_x , e_y , e_ψ .

$$\begin{aligned} \dot{V}_x &= -A_1 V_x + (B_1 - V_x) f(e_x) - (D_1 + V_x) g(e_x) \\ \dot{V}_y &= -A_2 V_y + (B_2 - V_y) f(e_y) - (D_2 + V_y) g(e_y) \\ \dot{V}_\psi &= -A_3 V_\psi + (B_3 - V_\psi) f(e_\psi) - (D_3 + V_\psi) g(e_\psi) \end{aligned} \quad (16)$$

A_i ($i = 1, 2, 3$) are nonnegative constants on behalf of the neurons of attenuation rate. B_i , D_i ($i = 1, 2, 3$) are considered nonnegative constants that denote the upper and lower bounds of neurons dynamic, which can restrict the outputs to $[-D_i, B_i]$.

Therefore, the proposed virtual speed controller is as follows:

$$\begin{aligned} \Gamma_u &= kV_x + u_L \cos V_\psi - v_L \sin V_\psi + V_y r_F \\ &\quad - l_d r_L \sin(\varphi_d + e_\psi) + \mu_1 \\ \Gamma_v &= kV_y - V_x r_F + u_L \sin V_\psi - v_L \cos V_\psi - dr_F \\ &\quad + l_d r_L \cos(\varphi_d + V_\psi) + \mu_2 \\ \Gamma_r &= r_L + k_3 V_\psi \end{aligned} \quad (17)$$

k, k_3 are the same parameters as (12). Based on the description above, V_x , V_y , V_ψ are all bounded and smooth without any sharp jumps when the inputs suddenly change.

3.3. Sliding-Mode Controller. After the virtual speed controller has been designed, a sliding-mode controller is introduced to produce the control force to make the USV arrive at the virtual speed.

Generally, the process of designing the sliding-mode controller is divided into two parts: defining a sliding manifold and designing a control law to move toward the sliding manifold.

The sliding manifold is selected as

$$s_1 = \Gamma_{eu} + \lambda_1 \int_0^t \Gamma_{eu}(\tau) d\tau \quad (18)$$

where $\Gamma_{eu} = u_F - \Gamma_u$ is the error between the reality surge velocity and the virtual velocity of the leader. From the derivation of (18), we can get

$$\dot{s}_1 = \lambda_1 \Gamma_{eu} + \dot{\Gamma}_{eu} = \lambda_1 (u_F - \Gamma_u) + \dot{u}_F - \dot{\Gamma}_u \quad (19)$$

let $\dot{s}_1 = 0$; we can get the equivalent control law

$$\begin{aligned} \tau_{uFeq} &= m_{11} \dot{\Gamma}_u - \lambda_1 m_{11} (u_F - \Gamma_u) - m_{22} v_F r_F + d_{11} u_F \\ &\quad - d_u \end{aligned} \quad (20)$$

Then, the switching control law can be selected as

$$\tau_{uFsw} = -\eta_1 \operatorname{sgn}(s_1) \quad (21)$$

We can obtain the surge force control law

$$\tau_{uF} = \tau_{uFeq} + \tau_{uFsw} \quad (22)$$

Next, the yaw control torque will be designed.

The yaw control torque is based on a two-order sliding manifold, and the sliding manifold is defined according to the sway speed error of the underactuated unmanned surface vehicles:

$$s_2 = \dot{\Gamma}_{ev} + 2\lambda_2 \Gamma_{ev} + \lambda_2^2 \int_0^t \Gamma_{ev}(\tau) d\tau \quad (23)$$

where $\Gamma_{ev} = v_F - \Gamma_v$ and λ_2 is a positive constant.

By derivation (23), we can get

$$\dot{s}_2 = \ddot{\Gamma}_{ev} + 2\lambda_2 \dot{\Gamma}_{ev} + \lambda_2^2 \Gamma_{ev} \quad (24)$$

$$\dot{\Gamma}_{ev} = \dot{v}_F - \dot{\Gamma}_v \quad (25)$$

$$\ddot{\Gamma}_{ev} = \ddot{v}_F - \ddot{\Gamma}_v \quad (26)$$

$$= -\frac{m_{11}}{m_{22}} (\dot{u}_F r_F + u_F \dot{r}_F) - \frac{d_{22}}{m_{22}} \dot{v}_F + \frac{\dot{d}_v}{m_{22}} - \ddot{\Gamma}_v$$

Considering the difficulty of computing $\ddot{\Gamma}_{ev}$, a feedback control input of acceleration error is introduced:

$$\ddot{\Gamma}_v = -k_v \dot{\Gamma}_v \quad (27)$$

let $\dot{s}_2 = 0$; then the equivalent control law can be designed as

$$\begin{aligned} \tau_{rFeq} &= -\frac{m_{22} m_{33}}{m_{11} u_F} \left(\frac{d_{22}}{m_{22}} \dot{v}_F - \frac{\dot{d}_v}{m_{22}} + k_v \dot{\Gamma}_v - 2\lambda_2 \dot{\Gamma}_{ev} \right. \\ &\quad \left. - \lambda_2^2 \Gamma_{ev} \right) - \frac{\dot{u}_F r_F m_{33}}{u_F} - (m_{11} - m_{22}) u_F v_F + d_{33} r_F \\ &\quad - d_r \end{aligned} \quad (28)$$

The switching control law is

$$\tau_{rFsw} = -\frac{m_{22}m_{33}}{m_{11}u_F} (\eta_2 \text{sgn}(s_2)) \quad (29)$$

so, the yaw control torque is

$$\tau_{rF} = \tau_{rFeq} + \tau_{rFsw} \quad (30)$$

The controller based on the backstepping method can be described as

$$\tau_{uj} = m_{1j} \left(-k_6 u_e - \frac{m_{2j}}{m_{1j}} v_j r_j + \frac{d_{1j}}{m_{1j}} u_j + \dot{u}_j^\alpha \right) \quad (31)$$

$$\tau_{rj} = m_{3j} \left(-k_7 r_e - \frac{m_{1j} - m_{2j}}{m_{3j}} u_j v_j + \frac{d_{3j}}{m_{3j}} r_j + \dot{r}_j^\alpha \right) \quad (32)$$

where u_j^α, r_j^α are virtual velocity controller.

4. Stability Analysis

We choose a Lyapunov function as

$$V_1 = \frac{1}{2} (e_x^2 + e_y^2 + e_\psi^2) + \frac{k}{2B} (V_x^2 + V_y^2) + \frac{k_3}{2B} V_\psi^2 \geq 0 \quad (33)$$

k, B , and k_3 are positive constants.

Let $V_{10} = (1/2)(e_x^2 + e_y^2) + (k/2B)(V_x^2 + V_y^2) \geq 0$, $V_{11} = (1/2)e_\psi^2 + (k_3/2B)V_\psi^2$.

Then,

$$\dot{V}_{10} = e_x \dot{e}_x + e_y \dot{e}_y + \frac{k}{B} (V_x \dot{V}_x + V_y \dot{V}_y) \quad (34)$$

Substituting (9) and (12) into (32), we can get

$$\begin{aligned} \dot{V}_{10} &= -ke_x V_x - ke_y V_y + \frac{k}{B} [V_x (-AV_x \\ &\quad + (B - V_x) f(e_x) - (D + V_x) g(e_x)) + V_y (-AV_y \\ &\quad + (B - V_y) f(e_y) - (D + V_y) g(e_y))] = -ke_x V_x \\ &\quad - ke_y V_y + \frac{k}{B} [-AV_x^2 - f(e_x) V_x^2 - g(e_x) V_x^2 \\ &\quad + Bf(e_x) V_x - Dg(e_x) V_x - AV_y^2 - f(e_y) V_y^2 \\ &\quad - g(e_y) V_y^2 + Bf(e_y) V_y - Dg(e_y) V_y] \\ &= -ke_x V_x - ke_y V_y + \frac{k}{B} [(-A - f(e_x) - g(e_x)) \\ &\quad \cdot V_x^2 + (Bf(e_x) - Dg(e_x)) V_x + (-A - f(e_y) \\ &\quad - g(e_y)) V_y^2 + (Bf(e_y) - Dg(e_y)) V_y] \end{aligned} \quad (35)$$

and if $B = D$,

$$\begin{aligned} \dot{V}_{10} &= -ke_x V_x - ke_y V_y \\ &\quad + \frac{k}{B} [(-A - f(e_x) - g(e_x)) V_x^2 \\ &\quad + k [f(e_x) - g(e_x)] V_x \\ &\quad + \frac{k}{B} [-A - f(e_y) - g(e_y)] V_y^2 \\ &\quad + k [f(e_y) - g(e_y)] V_y \\ &= \frac{k}{B} [(-A - f(e_x) - g(e_x)) V_x^2 \\ &\quad + k [f(e_x) - g(e_x) - e_x] V_x \\ &\quad + \frac{k}{B} [-A - f(e_y) - g(e_y)] V_y^2 \\ &\quad + k [f(e_y) - g(e_y) - e_y] V_y \end{aligned} \quad (36)$$

In the same way,

$$\begin{aligned} \dot{V}_{11} &= e_\psi \dot{e}_\psi + \frac{k_3}{B} V_\psi \dot{V}_\psi \\ &= -k_3 e_\psi V_\psi + \frac{k_\psi}{B} [-A - f(e_\psi) - g(e_\psi)] V_\psi^2; \end{aligned} \quad (37)$$

as defined in (14), if $e_i \geq 0$, then $f(e_i) = e_i, g(e_i) = 0, A + f(e_i) + g(e_i) = A + e_i > 0, f(e_i) - g(e_i) - e_i = e_i - e_i = 0$.

If $e_i < 0$, then $f(e_i) = 0, g(e_i) = -e_i$,

$$\begin{aligned} A + f(e_i) + g(e_i) &= A - e_i > 0, \\ f(e_i) - g(e_i) - e_i &= e_i - e_i = 0. \end{aligned} \quad (38)$$

We can determine that $A + f(e_i) + g(e_i)$ is a positive constant and $f(e_i) - g(e_i) - e_i$ equal to 0. So, $\dot{V}_{10} < 0, \dot{V}_{11} < 0$; therefore $\dot{V}_1 = \dot{V}_{10} + \dot{V}_{11} < 0$, so V_1 is monotonically decreasing and $\lim_{t \rightarrow \infty} V_1 = 0$; we can obtain $\lim_{t \rightarrow \infty} e_x = 0, \lim_{t \rightarrow \infty} e_y = 0, \lim_{t \rightarrow \infty} e_\psi = 0$. Based on Lyapunov stability, the outer loop is stable.

To guarantee the surge speed $u_F \rightarrow \Gamma_u$, a candidate Lyapunov function is chosen as follows:

$$V_2 = \frac{1}{2} m_{11} s_1^2 \quad (39)$$

and, then, derivation of (36),

$$\dot{V}_2 = m_{11} s_1 \dot{s}_1 = -\eta_1 |s_1| < 0 \quad (40)$$

where η_1 is a positive constant. This means that s_1 has asymptotic stability, so the trajectory can reach the origin, $\Gamma_{eu} \rightarrow 0, u_F \rightarrow \Gamma_u$.

Choose another Lyapunov function as

$$V_3 = \frac{1}{2} m_{22} m_{33} s_2^2 \quad (41)$$

With Assumption 1, we can get

$$\dot{V}_3 = m_{22} m_{33} s_2 \dot{s}_2 = -\frac{m_{22} m_{33}}{m_{11} u_F} \eta_2 |s_2| < 0 \quad (42)$$

Therefore, s_2 is asymptotic stability, $\Gamma_{ev} \rightarrow 0$, $v_F \rightarrow \Gamma_v$. The surge speed and sway speed of unmanned surface vehicles are bounded, which has been proven above, and the yaw angle speed is also bounded, which will be verified below.

Consider the augmented Lyapunov function:

$$V_4 = \frac{1}{2} m_{33} r_F^2; \quad (43)$$

then,

$$\begin{aligned} \dot{V}_4 &= m_{33} r_F \dot{r}_F \\ &= r_F ((m_{11} - m_{22}) u_F v_F - d_{33} r_F + \tau_{rF} + d_r) \end{aligned} \quad (44)$$

If $(m_{11} - m_{22}) u_F v_F + \tau_{rF} + d_r < d_{33} r_F$ is satisfied, then $\dot{V}_4 < 0$, V_4 is a decreasing function. Since $V_4 = (1/2) m_{33} r_F^2 \geq 0$, r_F is also decreasing and the largest value must exist. u_F , v_F , τ_{rF} is bounded, which has been proven above, and d_r is also bounded, as clarified in Assumption 3, so r_F must be bounded.

5. Simulation Results and Analysis

5.1. Straight Line Formation Control. To verify the effectiveness of the proposed strategy, the mathematical value of 3 USVs is used for simulation from [23].

$m_{11} = 120 \times 10^3 \text{ kg}$, $m_{22} = 217.9 \times 10^3 \text{ kg}$, $m_{33} = 636 \times 10^5 \text{ kg}$,
 $d_{11} = 215 \times 10^2 \text{ kg} \cdot \text{s}^{-1}$, $d_{22} = 117 \times 10^3 \text{ kg} \cdot \text{s}^{-1}$, $d_{33} = 802 \times 10^4 \text{ kg} \cdot \text{s}^{-1}$.

A simple case of straight line formation control is considered first. In the simulation, USV 2 and USV 3 are followers; USV 1 is a virtual leader. The system initial state is as follows: $\eta_2 = [0.1, 2, \pi/2]^T$, $\eta_3 = [2, -5, \pi/2]^T$; the desired position and orientation with respect to USV 1 are as follows: $ld_{12}=5\text{m}$, $ld_{13}=5\text{m}$, $\varphi_{d12} = \pi/2$, $\varphi_{d13} = -\pi/2$. We select $k_1=k_2=k_3=3$, $A_1=A_2=A_3=4$, $B_1=D_1=6$, $B_2=D_2=5$, $B_3=D_3=5$, $\lambda_1 = 1$, $\eta_1 = 150$, $\lambda_2 = 1.3$, $\eta_2 = 300$. The disturbance is defined as time-varying disturbance $\mathbf{W} = 4 \times 10^3 [\sin(0.2t), 1 + 2 \sin(0.3t), 2]^T$.

The motion curve of three USVs under the proposed scheme is shown in Figure 2. As seen from Figures 2–4, at first, the leaders adjust their control input, making them approach the desired distance and orientation. After a few seconds, the leader and the follower have reached the desired index. During this procedure, we can see from Figure 3 that the yaw angle changes slowly; this is attributed to the bioinspired model constraining the control input when the initial error was large and included the coordinate transformation of the control point. Figure 4 shows that the control input of the

FIGURE 2: The USV motion curve of straight line formation.

USV is smooth and different from the traditional method in [24]. As the controller based on the backstepping approach, this controller causes the sharp speed jumps when tracking errors change suddenly at initial time. For example, the surge speed of the backstepping method jumps to more than 10 m/s, but the biological inspired method is just about 5 m/s in Figures 5 and 6. Therefore, the proposed bioinspired method is more practical and effective.

5.2. Circular Formation Control. A typical circular path was studied in this section. The initial state $\eta_1 = [0.1, 0.1, \pi/4]^T$, $\eta_2 = [6, 0.1, 0.1]^T$, $\eta_3 = [0.1, 6, \pi/2]^T$. The desired distance and orientation are $ld_{12}=8\text{m}$, $ld_{13}=8\text{m}$, $\varphi_{d12} = \pi/2$, $\varphi_{d13} = -\pi/2$. We select $k_1 = k_2 = k_3 = k = 1$, $A_1 = A_2 = A_3 = 8$, $B_1 = D_1 = 10$, $B_2 = D_2 = 6$, $B_3 = D_3 = 6$. $\lambda_1 = 1.6$, $\eta_1 = 200$, $\lambda_2 = 1$, $\eta_2 = 200$. The disturbance is defined as time-varying disturbance $\mathbf{W} = 4 \times 10^3 [\sin(0.2t), 1 + 2 \sin(0.3t), 2]^T$. The simulation results are as shown in Figures 5–7. We can also see that, after the first 20 seconds, the followers USV 2 and USV 3 produce a control force and torque based on the bioinspired hybrid control method, making them move in the error-decreasing direction. Though the distance error and orientation error are large at first, the control input changes slowly in the first few seconds, which leads to the error tending toward zero at a reasonable speed in Figures 8 and 9.

6. Conclusion and Future Work

The development of a bioinspired model-based hybrid sliding-mode formation controller for underactuated unmanned surface vehicles has been presented. The kinematics and dynamic equation of USV formation are first established; then a bioinspired-based, sliding-mode hybrid control strategy, including a virtual speed controller

FIGURE 3: The position and attitude of the three USV.

FIGURE 4: The force and torque of USV 2 and USV 3.

FIGURE 5: The velocity of USV with the proposed method.

and a sliding-mode controller, is proposed. The stability and effectiveness of the controller have been proven by the Lyapunov theory and verified through MATLAB simulation. The controller addresses the problem of speed jump and controller saturation caused by the large initial error and guarantees yaw angle stability through coordinate transformation. However, collision avoidance and communication between the follower and the leader

should be considered in future work. In addition, distributed formation control and constrained control of underactuated marine vehicles are also highly desirable; related research is most concerned with the full actuated surface vehicles so far [25, 26].

FIGURE 6: The velocity of USV with backstepping method.

FIGURE 7: The USV motion curve of straight line formation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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FIGURE 8: The force and torque of USV 2 and USV 3.

FIGURE 9: The position and attitude of the three USV.

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