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Sliding mode fuzzy control-based path-following control for a dolphin robot

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Dolphins are one of the most enigmatic sea creatures in the world. Long-term evolution endows them with excellent swimming skills, which motivate researchers and engineers to create an innovative biomimetic propulsive mechanism that could replace traditional screw propellers for underwater exploration [1–3]. However, an important control problem arises with regard to path-following capability [4]. The major challenges associated with designing a robust tracking control method for underwater vehicles mainly exist in the highly nonlinear behavior of the vehicles, imprecise hydrodynamic coefficients, and external environmental disturbances [5]. In this article, we propose a control approach for the dolphin robot to follow a predefined path, involving a Line-of-Sight (LOS)-based planner, a sliding mode controller, and a fuzzy strategy.

LOS-based sliding mode fuzzy control.

- LOS guidance law. Figure 1(a) depicts the geometry illustration of the LOS guidance law for a dolphin robot to follow a general path. Here, a geometrical path, Ω, is defined on the 2-D surface, which is represented by a scalar variable θ. For any given θ, the inertial position of the geometric path is denoted by $p_d(\theta) = (x_d(\theta), y_d(\theta))$.

Consider a circle with the center located in the center of gravity of the dolphin. If the radius of the circle, R, is chosen to be sufficiently large, the circle will intersect the path tangentially at two points. The foresight point is set as $p_{\text{los}}(x_{\text{los}}, y_{\text{los}})$. The desired yaw angle can be obtained.

$$\psi_d = \chi_p - \text{atan2}(e, \Delta) - \text{atan2}(v, u), \tag{1}$$

where χ_p is the path-tangential angle, e is the cross-track error which is computed as the orthogonal distance from the dolphin robot's position to the target in the inertial frame.

$$e = -(x(t) - x_d)\sin(\chi_p) + (y(t) - y_d)\cos(\chi_p). \tag{2}$$

- Sliding mode control. As for the dolphin robot, path following refers to the case where it is sufficient to have nonzero forward speed and to use its flippers to force the yaw angle, ψ, to converge to the desired course angle, ψ_d. Thus, the tracking error vector can be defined as follows:

$$\psi_e = \psi - \psi_d. \tag{3}$$

In order to drive the tracking error vector to zero, a time-varying surface, $S(t)$, is defined by a scalar equation $s(\psi, t)$ in terms of the yaw error as follows:

$$s_\psi = \lambda_\psi \psi_e + \dot{\psi}_e, \tag{4}$$

where λ_ψ consists of strictly positive constants determining the slope of the sliding surfaces. A requirement of this method is that when $t \to \infty \Rightarrow s \to 0$. The sliding mode may be defined as $\dot{s}_\psi = 0$. Defining sliding surfaces as $s_\psi = 0$, the Lyapunov

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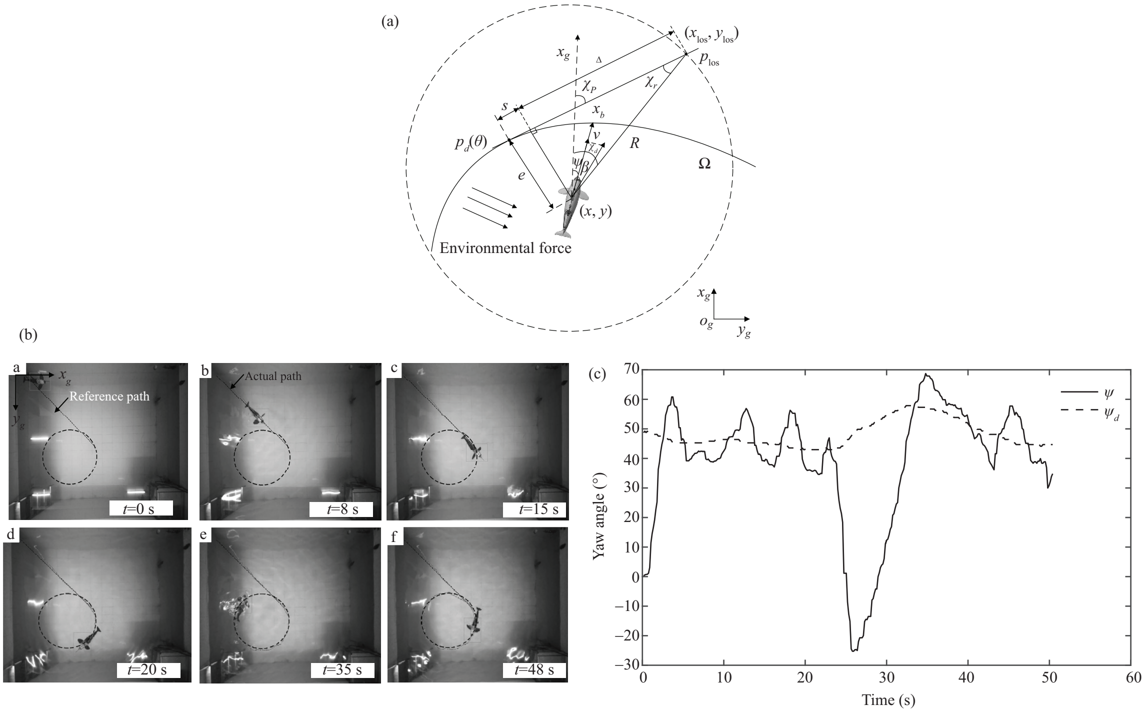

Figure 1 (a) Schematic of the LOS guidance geometry for a general path; (b) snapshot of the dolphin robot performing path following. The dotted line represents the reference path while the line represents the actual path; (c) result of the anti-interference experiment.

function candidate is defined by taking the following form:

$$V(s_\psi) = \frac{1}{2}{s_\psi}^2. \tag{5}$$

To provide the asymptotic stability of (5) about the equilibrium point $s_\psi = 0$, the following conditions must be satisfied:

(1) When $s_\psi \neq 0$, $\dot{V}(s_\psi) < 0$;

(2) $\lim_{|s_\psi| \to \infty} V(s_\psi) = \infty$.

Evidently, condition (2) is met. To achieve a finite-time convergence (i.e., global finite-time stability), the derivative of the Lyapunov function candidates should be satisfied

$$\dot{V}(s_\psi) = s_\psi \dot{s}_\psi < 0. \tag{6}$$

If (6) is satisfied, the sliding mode may be defined as $\dot{s}_\psi = 0$. Because $\dot{s}_\psi = \lambda_\psi(\dot{\psi} - \dot{\psi}_d) + (\ddot{\psi} - \ddot{\psi}_d)$, we can obtain

$$\begin{aligned} M_{r,\mathrm{eq}} &= \hat{m}_{33}\ddot{\psi}_d + \hat{d}_{33}r + (\hat{m}_{22} - \hat{m}_{11})\,uv \\ &\quad + \lambda_\psi \hat{m}_{33}(\dot{\psi}_d - r), \end{aligned} \tag{7}$$

where $M_{r,\mathrm{eq}}$ is the estimation of the equivalent control. "ˆ" represents the estimated hydrodynamic coefficients of the dolphin robot.

To eliminate chattering, we set the switching controller as sat$\,(s)$, thereby transforming the discontinuous control law to a thin neighboring boundary layer. The continuous control law can be defined when the system achieves the sliding mode surface.

$$\begin{aligned} M &= \hat{m}_{33}\ddot{\psi}_d + \hat{d}_{33}r + (\hat{m}_{22} - \hat{m}_{11})uv \\ &\quad + \lambda_\psi \hat{m}_{33}(\dot{\psi}_d - r) - k_1 \mathrm{sat}(s_\psi), \end{aligned} \tag{8}$$

where k_1 is a positive value that has contact with a positive value δ_1.

- Fuzzy logic controller. The output forces/moments from sliding mode control cannot directly distribute to control surfaces because the relation between deflection angles and resultant yaw moments is nonlinear, especially when the flippers rotate in a wide angular range [6]. There is no appropriate mathematical model to denote the turning motion of the dolphin robot. Fuzzy logic, which is much closer in spirit to human thinking and natural language than traditional logical systems, has provided an effective means of converting the linguistic control strategy based on expert knowledge into an automatic control strategy.

Experiments and analysis. To evaluate the path-following performance and the effectiveness/robustness of the proposed control methods, extensive aquatic experiments were conducted in an indoor pool. To obtain the real-time position of the dolphin robot, a global camera installed on the ceiling is employed [7].

- Path-following experiment. The first experiment was intended to examine path-following performance. As for the linear equation, the starting and stopping point were denoted as (0,0) and $p_{d1}(\theta) = (2.4, 2.4)$, respectively. The inertial position of the circular path was defined $p_{d2}(\theta) = (0.9\cos\theta + 1.5, 0.9\sin\theta + 2.4)$.

The snapshot sequences of the path-following experiment captured by the global camera are shown in Figure 1(b). It took the dolphin robot approximately 5 s to approach and follow the straight line. When $t = 15$ s, the robot reached the switching point, $p_{d1}(\theta)$. Then, after approximately 33 s, the dolphin robot completed the circular path-following process. The results show that the proposed control methods successfully steered the robot toward and along the desired path.

- Anti-jamming experiment. To verify the robustness and stability of the proposed sliding mode fuzzy control (SMFC) method, an anti-jamming experiment was conducted and the corresponding data is presented in Figure 1(c). During the test, the robot was steered to follow the straight line defined in the aforementioned experiment. The robot converged to the desired path after 15 s, an external disturbance was suddenly imposed on the robot at $t = 25$ s, and the robot was knocked out of its orbit. Thanks to the proposed SMFC method, the dolphin was forced to follow the predetermined path after approximately 20 s and it remained on the target path. The experiment verified the robustness of the proposed control scheme.

- Discussion. Owing to the LOS-based SMFC method, the dolphin robot could converge towards and follow the desired path. The first experiment also covers a heading switching experiment that is combined with the anti-jamming experiment to demonstrate the finite-time stability and robustness of the system.

Conclusion and future work. In this article, we have presented a sliding mode fuzzy strategy for the path-following control of a dolphin robot. Specifically, the LOS-based planner is proposed to acquire the desired yaw angle. A sliding mode controller is designed to make sure the dolphin robot arrive at the next position timely and accurately. Furthermore, a fuzzy logic controller is utilized to establish the mapping relations between yaw moment from the sliding mode controller and actual control signals for the dolphin robot. Finally, the experimental results validate the effectiveness of presented path-following control methods for the dolphin robot.

The ongoing and future work will focus on the three-dimensional path-following control problem for the dolphin robot in wider waters.

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