Adaptive Fuzzy Planar Path Following Control for Underactuated Wave Glider

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Abstract. This paper addresses a path following problem of wave glider along a predefined path in horizontal plane. Based on the LOS guidance law and the virtual target method, a planar guidance controller for underactuated wave glider is presented to ensure the stability of the path following. And then, according to the classic feedback linearization PID controller and fuzzy controller, a fuzzy adaptive PID controller is developed. Furthermore, analysing the typical application scenario of wave glider, we set a simulation path in horizontal plane named polyline path. Numerical simulation results illustrate the proposed control design is effective to deal with planar following problem of wave glider.

1. Introduction
In this paper, combined with the two-layered control of planar path guidance law and fuzzy logic PID control, an adaptive fuzzy PID controller is proposed to regulate the planar path following for underactuated wave glider subject to uncertainties. In the first layer, the guidance controller based on the LOS guidance algorithm is presented to ensure the stability of wave glider following the predefined path. According to the current status information, the guidance controller passes the path following variable to the second layer. In the second layer, according to the classic feedback linearization PID controller and fuzzy controller, an adaptive fuzzy PID controller is developed. A fuzzy logic method is adopted to adjust the PID gains adaptively to improve the robustness of the system under uncertain parameters and time-varying environmental disturbances. Furthermore, by adopting the sensitivity analysis with the numerical

2. Problem statement
This section describes the kinematics and dynamics of the wave glider in horizontal plane, and presents the motion control problem of planar path following for underactuated wave glider.
As illustrated in Fig.1, \{I\} denotes the inertial frame fixed on the earth, \{B\} denotes the body-fixed frame and \{SF\} denotes Serret-Frenet frame. The \(x\)-axis of \{SF\} is along the tangential of the following path and the \(y\)-axis of \{SF\} is along the normal of the following path. Let \(P\) be the center of gravity of wave glider, \(P = [x, y, z]^T\) denotes the position of the point \(P\) in \{I\}, \(\Theta = [\phi, \theta, \psi]\) and denotes the orientation of the point \(P\) in \{I\}. \(\mathbf{v} = [u, v, w]^T\) is the vector of the wave glider’s velocities expressed in \{B\}. \(\mathbf{\omega} = [p, q, r]\) is the vector of the wave glider’s angular velocities expressed in \{B\}.

Referring to the simplified approach to the dynamics model in [1, 11-13], considering the path following algorithm in the horizontal plane, we can ignore the heave, pitch and roll of the hull. The dynamics model of wave glider can be simplified as a kinematics and kinetics model of path following in the horizontal plane [3, 11, 16].

The kinematics equations

\[
\begin{align*}
\dot{x} &= u \cos(\psi) - v \sin(\psi) \\
\dot{y} &= u \sin(\psi) + v \cos(\psi) \\
\dot{\psi} &= r
\end{align*}
\]

The kinetics equations

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
m_{22} & -d_{11} & \frac{r_u + \tau_{ur}}{m_{11}} \\
-d_{22} & m_{22} & \frac{r_v + \tau_{vr}}{m_{33}} \\
\frac{r_u - \tau_{ur}}{m_{33}} & \frac{r_v - \tau_{vr}}{m_{33}} & m_{33}
\end{bmatrix} \begin{bmatrix}
u \\
v \\
r
\end{bmatrix} + \begin{bmatrix}
d_{11}u \\
d_{22}v \\
\end{bmatrix} \mathbf{v} - \begin{bmatrix}
d_{11}r \\
-d_{22}r
\end{bmatrix} \mathbf{\omega}
\]

Where \(m_{(i)}\) express the combined rigid-body and added mass terms, \(d_{(i)}\) denotes the linear and quadratic drag terms coefficients.
There are usually two types of motion control problems: trajectory tracking and path following. Wave glider are under-actuated surface vessels, the surge velocity \( u \) of wave glider is directly related to the marine environment and cannot be controlled. Thus, only path following strategy is considered in this paper.

As depicted in Fig.1, a wave glider follows a predefined planar curve path \( S \), where the curve path can be continuously parameterized by a scalar variable \( s \), and denote the inertial position of the path \( S \) as \( P_p(s) = [x_p(s), y_p(s)]^T \in \mathbb{R}^2 \). \( P_p \) is a virtual moving point on the path \( S \), which is used as a virtual target point for the path following. The path frame \( \{SF\} \) can be built according to the virtual moving point \( P_p \). Define \( e = [x_e, y_e]^T \) as the path following error vector between \( P \) and \( P_p \) in frame \( \{SF\} \), where the along track error \( x_e \) represents the distance from wave glider to the desired position of the virtual target point \( P_p \) in the \( x \)-axis of \( \{SF\} \), the cross track error \( y_e \) represents the distance along the \( y \)-axis of \( \{SF\} \) [17].

The problem of planar path following control for wave glider can be formulated as follows: Given a predefined planar path \( S \) (continuous, differentiable and bounded), develop robust feedback control laws for external forces and torque angle acting on wave glider, such that its center of gravity \( P \) asymptotically converges to the virtual reference point \( P_p \) and moves along the planar path \( S \).

### 3. Horizontal Plane path following control

![Figure 2. Fuzzy PID controller of planar path following.](image)

The block diagram of path following controller in horizontal plane is shown in Fig 2. The controller consists of two layers: the line-of-sight guidance algorithm and the fuzzy PID controller. The desired angle \( \psi_d \) obtained through the LOS guidance law is defined as the input parameter of the fuzzy PID controller. Using fuzzy inference method to implement online adaptive adjustment of PID controller’s gains, and provides a robust control of underactuated wave glider influenced by environmental disturbances and parameter uncertainties. Combining the LOS guidance algorithm and fuzzy PID controller, the planar path following controller of wave glider is established.

### 4. Numerical Simulations

In order to illustrate the performance of the designed controller, the numerical simulations are carried out, and the simulation parameters adopt geometric dimension parameters and hydrodynamic coefficients in. In this paper, the effectiveness of the path following controller is verified through the use of the polyline path. This is the main type of predefined path in practice, and can well reflect the controller’s performance.

Unmanned surface vessels, such as wave glider, often observe a specific area by comb-shaped trajectories. Therefore, through the simulation of polyline path, the controller’s linear tracking...
accuracy along the path and after the inflection point can be illustrated obviously. A reference polyline path can be described as follows:

\[
\begin{align*}
    x(s) &= s & \quad & s \in [0, 100] \\
    y(s) &= s
\end{align*}
\]

\( (3) \)

\[
\begin{align*}
    x(s) &= s & \quad & s \in [100, 200] \\
    y(s) &= 200 - s
\end{align*}
\]

\( (4) \)

Where the initial point of wave glider is \((10, 0)\), the inflection point of the polyline is \(P_T = (100, 100)\).

When wave glider moves along the first segment polyline (3), the distance \(R\) between the current position \(P\) and the inflection point \(P_T\) is calculated in real time. When \(R < 10\), the reference path is switched to the second segment polyline. The predefined polyline and the actual trajectory of the wave glider are shown in Fig 3 (a), it is observed that the wave glider converges to the reference path rapidly without obvious overshoot. The desired heading \(\psi_d\) generated by the LOS guidance law and the actual heading \(\psi\) are depicted in Fig 3 (b). Obviously, the actual angle \(\psi_d\) can perfectly follow the desired angle \(\psi\) in the early stages of control. Fig 3(c) shows the curve of the rudder angle, the maximum rudder angle \(R_{\text{max}} = 40\text{(degree)}\) and the minimum rudder angle \(R_{\text{min}} = 40\text{(degree)}\) is appeared in 11s and 289s, the extreme value of rudder angle is due to the supersaturating of the rudder. The curves of surge speed \(u\), sway speed \(v\) and yaw rate \(r\) in the course of path following are shown in Fig 3(d). In Fig 3 (e)-(f), we can find the cross track error and the along track error converge to zero smoothly rapidly. Fig 3 (g) shows the process of adaptive adjustment of three parameters of adaptive fuzzy PID controller.
5. Conclusions and future work
In this paper, an adaptive fuzzy planar path following control for underactuated wave glider is proposed. Based on the LOS guidance algorithm and fuzzy PID controller, the two layer control framework for planar path following is depicted. We design a typical form of reference path as polyline path, and the performance of the controller are analyzed by numerical simulation. The simulation results show the performance meets the requirements of the path following accuracy.

References
[1] Lekkas A. A Quaternion-Based LOS Guidance Scheme for Path Following of AUVs. Control Applications in Marine Systems 2013. p. 245-50.
[2] Lekkas AM, Fossen TI. A Time-Varying Lookahead Distance Guidance Law for Path Following. Maneouvring and Control of Marine Craft2012. p. 398-403.
[3] Liu L, Wang D, Peng Z, Wang H. Predictor-based LOS guidance law for path following of underactuated marine surface vehicles with sideslip compensation. Ocean Engineering. 2016; 124: 340-8.
[4] Garus J, Zak B. Using of soft computing techniques to control of underwater robot. International Conference on Methods and MODELS in Automation and Robotics2010. p. 415-9.
[5] Xiang X, Lapierre L, Jouvencel B. Smooth transition of AUV motion control: From fully-actuated to under-actuated configuration. Robotics and Autonomous Systems. 2015; 67: 14-22.
[6] Zhu D, Sun XHB. A Neurodynamics Control Strategy for Real-Time Tracking Control of Autonomous Underwater Vehicles. Journal of Navigation. 2014; 67: 113-27.
[7] Bessa WM, Dutra MS, Kreuzer E. Depth control of remotely operated underwater vehicles using an adaptive fuzzy sliding mode controller. Robotics & Autonomous Systems. 2008; 56:
[8] Ishaque K, Abdullah SS, Ayob SM, Salam Z. A simplified approach to design fuzzy logic controller for an underwater vehicle. Ocean Engineering. 2011; 38: 271-84.

[9] Børhaug E, Pettersen KY. Cross-track control for underactuated autonomous vehicles. Decision and Control, 2005 and 2005 European Control Conference Cdc-Ecc ’05 IEEE Conference on2006. p. 602-8.

[10] Kraus ND. Wave glider dynamic modeling, parameter identification and simulation: University of Hawaii; 2012.

[11] Do KD, Pan J. Control of ships and underwater vehicles: design for underactuated and nonlinear marine systems: Springer; 2009.

[12] Fossen TI. Handbook of Marine Craft Hydrodynamics and Motion Control. 2011.

[13] Nie W, Feng S. Planar path-following tracking control for an autonomous underwater vehicle in the horizontal plane. Optik-International Journal for Light and Electron Optics. 2016; 127: 11607-16.

[14] Xiang X, Yu C, Zhang Q. Robust fuzzy 3D path following for autonomous underwater vehicle subject to uncertainties. Computers & Operations Research. 2016.

[15] Pavlov A, Nordahl H, Breivik M. MPC-Based Optimal Path Following for Underactuated Vessels. Ifac International Conference on Manoeuvring and Control of Marine Craft2009. p. 340-5.

[16] Li D, Fu Y, Yang L. Coupling dynamic modeling and simulation of three-degree-of-freedom micromanipulator based on piezoelectric ceramic of fuzzy PID. Modern Physics Letters B. 2017: 1750140.