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Research article

Heading tracking control with an adaptive hybrid control for under actuated underwater glider

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ABSTRACT

The underwater glider changes its direction to follow the preset path in the horizontal plane only by flapping its vertical rudder. Heading tracking control plays the core role in the navigation process. To deal with non-linear flow disturbance and saturation in actuator, a new hybrid heading tracking control algorithm was presented, which integrated an adaptive fuzzy incremental PID (AFIPID) and an anti-windup (AW) compensator to improve the adaptability and robustness of underwater glider's heading control. The dynamic model of an underwater glider named as Petrel-II 200 was modeled to serve as a controlled plant. The proposed heading tracking control algorithm was described in detail, where the rudder angle, a control quantum to the controlled plant were calculated to get forces and moments required for the desired glider heading. A closed loop motion control system with desired heading angle as input and actual heading angle output was put forward, which included the dynamic model of the Petrel-II 200 and the given heading tracking control algorithm. The simulations followed three typical mathematical signals and the experimental tests were carried out by taking in the dynamic parameters of the controlled plant. And the effectiveness of the proposed control algorithm was assessed and verified.

1. Introduction

Autonomous underwater gliders (AUGs) are widely applied to perform various tedious and risky missions in military, scientific, civil as well as commercial areas such as oceanographic mapping, search for naval resources etc. [1]. However, the capabilities of long range time operation without supervision present a main challenge in the development of advanced AUGs, that the navigation control of the vehicle must be capable of safely and effectively guiding the AUG in dynamic and cluttered ocean environments [2]. Thus it is necessary to design a robust control strategy to perform precise navigation, which makes the AUG cruise on a planned path with pre-defined heading [3–5]. Heading tracking control plays the core role in the navigation process for under actuated underwater gliders. It reflects the possibility of a planned behavior during a mission using all present and future information about the area of operation [6]. Performing precise heading control of an AUG is a formidable task because of model nonlinearities, actuator saturations and time-varying disturbances [5].

Adaptive control has been much developed to deal with these nonlinearities in the past decade [7–15]. For model nonlinearities, various approaches have been proposed with adaptive controls, such as fuzzy control [7,8,15], neural network control [11] and adaptive backstepping control [10,13]. A hybrid control with PID and neural networks was used for an AUV to manage heading control [14]. This approach can find a robust solution when disturbances exist. An adaptive fuzzy PID control algorithm was presented to solve the uncertainties of PID parameters and the model of AUV [15]. Form the simulation results, it could be seen that the convergence time with a 20 amplitude step signal input using the proposed algorithm was 60 s, the overshoot was 7.05% and the undershoot was about 9.55%, which showed good performances in heading control. An adaptive sliding mode control based on a disturbance observer was designed for heading control of AUVs [5]. The nonsymmetrical dead-zone with unknown parameters and input saturation was considered in the adaptive heading control. Compared with traditional PID and sliding mode control, the adaptive sliding mode control has better performances in tracking step signal heading with much low errors. To dealing with input saturation problems, anti-windup design [16–20] has been developed. A hybrid control combined a model reference adaptive control and a modern anti-windup compensator (AW) was proposed to realize the heading control of an AUV in the presence of input saturations and uncertain dynamics [17]. A modern AW compensator was added to a model

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Table 1
Relevant methods for underwater vehicle control.

Method	Time domain performance	Main feature
Traditional PID [7,8]	Obvious overshoot and oscillation; long convergence time; introduced time delay	Simplicity; bad robustness
Conventional Fuzzy	Relatively small overshoot and declined oscillation	Good robustness; declined control precision with simple fuzzy processing
FNN [11]	Comparably short convergence time; improved resistance against disturbance	Approximation accuracy for systematic nonlinearity was improved
AC [3]; DB [10]	No overshoot or oscillation	without considering environment disturbance
FASMC [9]; DCHM [12]; NNPID [14]; AFPID [15]; FPID [8]; VSPID + AW [19]	No oscillation; still has overshoot phenomenon	Good adaptability and improved robustness
VSPID [31]	Slight overshoot phenomenon	Prevention of integrator windup; Big energy consumption due to frequent regulation of the actuator
LQ + RBAW [20]	Slight steady-state error with rectangle input	Restricted effect of input saturation
APID + AW [17]	Overshoot was reduced but was not eliminated	AW was used to settle actuator saturation
ASMC [5]	Overcome the overshoot phenomenon	Big heading error was not considered
MRAC + AW [18]	Slight overshoot phenomenon	Actuator saturation was considered; only be validated by simulation
AFIPID + AW	No overshoot and desirable heading tracking performance	No limitations (at current research)

reference adaptive PID controller for underwater vehicles, various simulations have been carried out in a nonlinear six degrees of freedom model [18]. A comparison of multivariable saturating control and AW control was also addressed in Ref. [16]. Table 1 summarizes underwater vehicle controls.

Although many adaptive controls dealing with nonlinearities and approaches using AW compensators have been successfully applied to underwater vehicles, heading tracking control performance with an AW compensator and the different types of desired heading tracking capabilities of AUGs are rare in existing literature. Besides, heading tracking capabilities including tracking a fixed heading and tracking a time-varying heading largely reflect the robustness and the adaptability of heading control algorithms. However, it is a well-known fact that disturbances caused by wind, wave and current are immeasurable and may depart the vehicle from a preset heading [14]. In some non-uniform flow situations, the influence of actuator saturation worked on underwater gliders is great. Thus, it is important and practical issue for heading tracking control of underwater gliders to deal with actuator saturation along with uncertain disturbance.

Combining an adaptive control with an AW compensator can be a convenient and practical way to deal with nonlinearities of AUGs. This paper puts forward a new model reference adaptive fuzzy incremental PID (AFIPID) control algorithm with an AW compensator. The proposed control algorithm is employed in heading tracking control of the Petrel-II 200.

2. Dynamics of the Petrel-II 200

To better appreciate the effect of the heading tracking control method and imitate the real glider in an unsteady, non-uniform flow field, the full dynamic model of the Petrel-II 200 was developed by combining rigid body dynamic equation with Hydrodynamic equation [21–25]. The Petrel-II 200, a kind of under actuated AUGs, was modeled as a rigid body with fixed wings and a tail immersed in a fluid with buoyancy control and controlled internal moving mass.

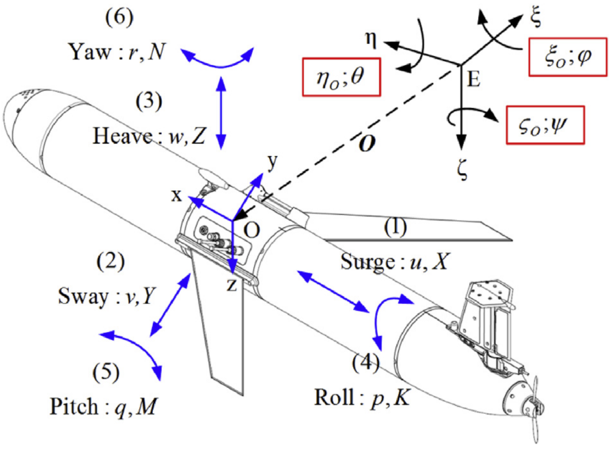

Fig. 1. The coordinate frame assignment of the Petrel-II 200.

The body coordinate frame O−xyz and the geodetic coordinate frame E−ηξς (i.e. the inertial frame) of the Petrel-II 200 are assigned, which is shown in Fig. 1. Let $\mathbf{O} = (\xi_O, \eta_O, \varsigma_O)^T$ be a position vector of the glider from the origin of the body coordinate frame to the origin of the geodetic coordinate frame. And assume $\boldsymbol{\Omega} = (\varphi, \theta, \psi)^T$ is an attitude vector of the glider in the geodetic coordinate frame, which is used for transformation from the body coordinate frame to the inertial frame. Besides, $\mathbf{O}$ and $\boldsymbol{\Omega}$ can also be used to describe the position and the attitude of the glider, which responds the six degrees of freedom (DOFs) in the following dynamic model of the Petrel-II 200. $\boldsymbol{\upsilon} = (u, v, w)^T$ and $\boldsymbol{\omega} = (p, q, r)^T$ are a transitional velocity vector and an angular velocity vector in the body coordinate frame, respectively. $\mathbf{F} = (X, Y, Z)^T$ and $\mathbf{T} = (K, M, N)^T$ are a transitional external force vector of the vehicle-fluid system and a total moment vector of the glider in the body coordinate frame, respectively.

The attitude transformation matrix $\mathbf{R}_{\mathrm{OE}}$ of the glider can be defined as:

$$\mathbf{R}_{\mathrm{OE}} = (\mathbf{x}_{\mathrm{OE}}\mathbf{y}_{\mathrm{OE}}\mathbf{z}_{\mathrm{OE}}) = \begin{pmatrix} x_{\mathrm{O}\xi} & y_{\mathrm{O}\xi} & z_{\mathrm{O}\xi} \\ x_{\mathrm{O}\eta} & y_{\mathrm{O}\eta} & z_{\mathrm{O}\eta} \\ x_{\mathrm{O}\varsigma} & y_{\mathrm{O}\varsigma} & z_{\mathrm{O}\varsigma} \end{pmatrix} = \begin{pmatrix} \cos\psi\cos\theta & \sin\varphi\cos\theta & \sin\varphi\sin\psi + \cos\psi\sin\theta\cos\varphi \\ -\sin\psi\cos\varphi + \cos\psi\sin\varphi\sin\theta & \cos\psi\cos\varphi + \sin\psi\sin\theta\sin\varphi & -\sin\psi\sin\theta\cos\varphi + \cos\psi\sin\varphi \\ \sin\psi\sin\varphi + \cos\psi\sin\theta\cos\varphi & \cos\psi\sin\varphi + \sin\psi\sin\theta\cos\varphi & \cos\theta\cos\varphi \end{pmatrix} \tag{1}$$