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Model reference adaptive PID control with anti-windup compensator for an autonomous underwater vehicle

Pouria Sarhadi, Abolfazl Ranjbar Noei, Alireza Khosravi *

Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran

HIGHLIGHTS

- A novel model reference adaptive PID control scheme is presented.
- An adaptive AW compensator is augmented to handle actuator saturation problem.
- The proposed method is applied to the nonlinear six DOF simulation of REMUS AUV.

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ABSTRACT

Model uncertainty and saturation in actuators are among some of the practical challenges in the controller design of autonomous vehicles. Incorporating adaptive control with anti-windup (AW) compensators can provide a convenient combination to counteract the challenge. In this manuscript, an adaptive control with a dynamic anti-windup compensator is proposed for an Autonomous Underwater Vehicle (AUV). Due to industrial and academic interests, the proposed method is embedded with a Proportional–Derivative–Integral (PID) controller. A modern AW technique is employed to cope with the saturation problem. Typical performance of the adaptive control system is achieved in the absence of actuator saturation. The performance is shown to degrade when the saturation has occurred. However the quality of the adaptive controller is improved when it is combined with an anti-windup compensator. Primarily six degrees of freedom (DOF) nonlinear motion equations of the vehicle are derived. Then, the proposed scheme is applied to this nonlinear model. Performance of the modified system is compared by the baseline controller. The effectiveness of the presented method in the presence of the actuator saturation, considering uncertainties, noise and disturbance is assessed and verified through simulation scenarios.

1. Introduction

Dealing with uncertain dynamics together with the actuator saturation are important and practical issues in the controller design of autonomous systems. In AUVs, due to the computational errors in obtaining hydrodynamic coefficients and varying the model parameters due to linearization in different operating points, usually the designer is faced by a model with uncertain parameters. Consequently adaptive control is an appropriate strategy to deal with these shortcomings whose applications are increasing in this field [1]. Furthermore, the actuator saturation problem is also among important factors that should be dealt with [2]. An interesting treatment is the use of the anti-windup technique. During the past decade this field is much developed [3–9]. Combining adaptive controller with a modern AW algorithm can be a convenient and practical way to deal with autonomous systems dynamics. This manuscript introduces a new type of model reference adaptive PID control with AW compensator. This method is employed in the pitch channel of an AUV in the presence of the actuator saturation.

Adaptive control in the presence of saturation is investigated in various researches [6,10–17]. Initial solutions including heuristic methods such as modifying the reference model [10] and hedging [11,12] are complemented with the stability analysis during the two past decades [13,15,16]. Currently, adaptive controllers with anti-windup compensator are still an open problem [6,8,18–22]. An AW approach for first and second order linear systems in [18], Model Reference Adaptive Control (MRAC) with AW feature for systems with actuator anomalies [19], adaptive anti-windup methods for nonlinear systems in Euler–Lagrange structure in [21,22]

* Corresponding author.
E-mail address: akhosravi@nit.ac.ir (A. Khosravi).

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are such recent works in this field. A use of combination of Recursive Least Squares (RLS) parameter estimator and a modern AW idea, in input saturated ship steering and Unmanned Aerial Vehicle (UAV) control are respectively reported in [6,23]. Meanwhile the adaptation has augmented to the modern AW compensators in [8,20]. According to the presented researches, anti-windup compensated adaptive control is one of the recent issues in the control literature.

AUV control is dealt with in several researches. For instance [24] applied a robust State Dependent Riccati Equation (SDRE) depth controller in an AUV. Adaptive back-stepping control is developed in [25] for a submarine model. Robust H_∞ Controller is designed for *Virginia Tech* 475 AUV in [26]. In [27], RISE feedback control is practically applied to control *SubjuGator* 7 AUV. Novel L_1 adaptive control is also implemented on AUVs in several Refs. [28–30]. In parallel, some researchers have tackled the actuator saturation problem in AUVs. In [31], a method based on solving linear matrix inequality (LMI) is provided to confront with the saturation. [32,33] have corrected PID and Proportional Integral (PI) controllers of underwater vehicles to prevent the integral windup. In [9], dynamic anti-windup controller is added to the Port-Hamiltonian feedback controller to deal with the input saturation. This is implemented on an Unmanned Underwater Vehicle (UUV). Due to occurrence of the actuator saturation problem in adaptive control, the investigation of application in autonomous systems should be considered [1]. This issue is discussed in this manuscript while the proposed method is implemented in a practical *REMUS* AUV model. Various simulations have been carried out in the nonlinear six degrees of freedom model. Performance of the controller is evaluated by applying uncertain conditions, disturbance and noise.

The rest of the paper is as follows. Section 2 presents the problem statement, nonlinear and linear model as well as uncertainties in the pitch channel of an AUV. Section 3 introduces structure of the model reference adaptive PID control. The work will be continued by applying anti-windup compensator. Simulation results and comparisons are addressed in Section 4. Finally, Section 5 closes the work by a conclusion.

2. Problem statement and six degrees of freedom model of AUV

As previously mentioned, the proposed method is implemented on a validated six DOF model of *REMUS* AUV [34]. Equations of motions of an underwater vehicle are investigated in various Refs. [34–36]. In this section, an overview of the equation is presented. Then an appropriate linear model for controller design is extracted. According to Fig. 1, vehicle translational and rotational motion vectors are defined as follows:

$$\eta=\begin{bmatrix}\eta_1\\ \eta_2\end{bmatrix}\quad \eta_1=\begin{bmatrix}x_r\\ y_r\\ z_r\end{bmatrix}\ \eta_2=\begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix}$$
$$v=\begin{bmatrix}v_1\\ v_2\end{bmatrix}\quad v_1=\begin{bmatrix}u\\ v\\ w\end{bmatrix}\ v_2=\begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{1}$$
$$\tau=\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}\quad \tau_1=\begin{bmatrix}X\\ Y\\ Z\end{bmatrix}\ \tau_2=\begin{bmatrix}K\\ M\\ N\end{bmatrix}.$$

In these equations, η denotes angles and positions of inertial coordinate, v stands for the linear and angular velocity in the body frame where τ shows input forces and moments of the vehicle. Table 1 defines parameters and variables according in Fig. 1:

The relationship between inertial and body frames is established by three rotations through conversion matrices of the body

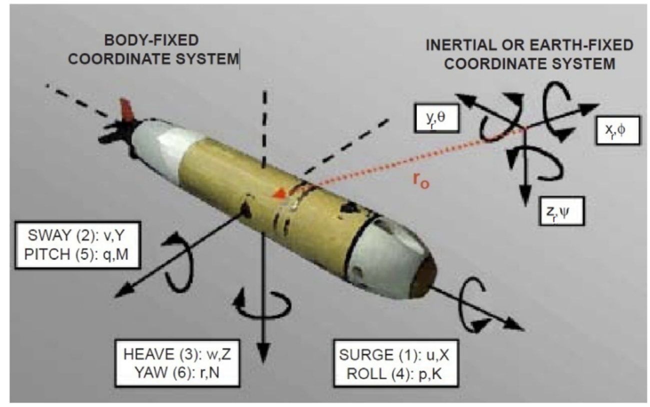

Fig. 1. The inertial and body coordinates reference frames of AUV.

to the inertial reference frames. The equations are separately written for linear and angular parameters:

$$\dot{\eta}_1=J_1(\eta_1)v_1 \qquad \dot{\eta}_2=J_2(\eta_2)v_2 \tag{2}$$

where:

$$J_1(\eta_1)=\begin{bmatrix}c\theta c\psi & -s\psi c\phi+c\psi s\theta s\phi & s\psi s\theta+c\psi c\phi s\theta\\ s\psi c\theta & c\psi c\theta+s\phi s\psi s\theta & -c\psi s\phi+s\theta s\psi c\phi\\ -s\theta & c\theta s\phi & c\theta c\phi\end{bmatrix}$$
$$J_2(\eta_2)=\begin{bmatrix}1 & s\phi t\theta & c\phi t\theta\\ 0 & c\phi & -s\phi\\ 0 & s\phi/c\theta & c\phi/c\theta\end{bmatrix} \tag{3}$$

in which $c(.)$, $s(.)$ and $t(.)$ denote cos(.), sin(.) and tan(.) trigonometric functions respectively. These equations are provided in order to introduce axes and the governing relationship to represent kinematic equations of motion. Dynamic equations must also be considered to complete the motion equations. The dynamic motion with six DOF equations for a rigid body are expressed as follows [36]:

$$\begin{aligned}
&m\left[\dot{u}-vr+wq-x_G(q^2+r^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})\right]=\sum X\\
&m\left[\dot{v}-wp+ur-y_G(r^2+p^2)+z_G(qr-\dot{p})+x_G(qp+\dot{r})\right]=\sum Y\\
&m\left[\dot{w}-uq+vp-z_G(q^2+p^2)+x_G(rp-\dot{q})+y_G(rq+\dot{p})\right]=\sum Z\\
&I_x\dot{p}+(I_z-I_y)qr+m\left[y_G(\dot{w}-uq+vp)-z_G(\dot{v}-wp+ur)\right]=\sum K\\
&I_y\dot{q}+(I_x-I_z)rp+m\left[z_G(\dot{u}-vr+wq)-x_G(\dot{w}-uq+vp)\right]=\sum M\\
&I_z\dot{r}+(I_y-I_x)pq+m\left[x_G(\dot{v}-wp+ur)-y_G(\dot{u}-vr+qw)\right]=\sum N
\end{aligned} \tag{4}$$

where parameters are defined in Table 1 and shown in Fig. 1. In these equations, the left side statements are related to the Newton's and Euler's rules for rigid body motion where the right hand side statements are related to input forces and moments at each direction. Forces and moments are resulted from the hydrostatic, hydrodynamic forces (lift and drag), added masses, thrust and control force. These are variably dependent on AUV geometrical form and motion conditions. Computation of these coefficients needs mechanical and hydrodynamics engineering knowledge which is out of the scope of this study. Combining AUV dynamics equations and adding the force and moment equations, provide the AUV model. Since the roll angle is bounded the pitch and the yaw angle is assumed decoupled. Nonlinear equations of motion in the pitch channel including q and θ states are expressed