Robust Controller Design for an Autonomous Underwater Vehicle

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Abstract

This paper presents a robust sliding mode control technique applied to an autonomous underwater vehicle. The sliding mode control is one of the most common nonlinear feedback controller design based on the Lyapunov analysis. Two common decoupled subsystems of an autonomous underwater vehicle are detailed. The role of the sliding mode control for the decoupled systems is to drive the system towards the designed slide surface and keep it on it. Therefore it is able to improve a capability to track the desired state of the proposed autonomous underwater model. Simulations of the heading and depth controls are demonstrated in this paper. The results have shown that the sliding mode control is able to provide accurate control for the system with small steady state errors.

Keywords: Robust control, Sliding mode, Autonomous Underwater Vehicles

1. Introduction

Autonomous Underwater Vehicle (AUV) is playing a vital role in underwater exploration allowing humans to explore great depths in various underwater environments. Many studies have considered the error correction in attitude and depth control for an autonomous underwater vehicle's system [1], [2]. Most stability criterions are formulated based on the Lyapunov method [3]. The method is a power tool for stability analysis which can be used for the design of the nonlinear controllers. One of the most common nonlinear feedback controller designs based on the Lyapunov analysis is the sliding mode control (SMC). It is categorised as a variable structure control system [3]. The SMC has been used for AUV control because of excellent stability, robustness and disturbance rejection characteristics [4], [5]. Fundamentally, the sliding mode controller is composed of two main parts, namely nominal part and discontinuous terms dealing with uncertainties. The controller with the typical sliding mode is to drive the system state error trajectory onto the sliding surface and maintain that trajectory onto the surface for all times. Thus, the sliding mode becomes insensitive to system disturbances whilst on the sliding surface. Furthermore the significant characteristics of the sliding mode are order reduction and robust stability [3].

This paper is organised as follows. Section 2 presents a model of an AUV. Section 3 describes the sliding mode controller design. Section 4 details decoupled subsystem of an AUV. Section 5 shows simulation results. Finally, section 6 presents the conclusion.

2. Model of an AUV

The system dynamics of AUVs are highly nonlinear, coupled and time varying which comes from many parameters, such as hydrodynamic drag, damping and lift forces, Coriolis and centripetal forces, gravity and buoyancy forces and forces from thrusters [4]. Fig. 1 depicts six components of different motions for a torpedo shape underwater vehicle.

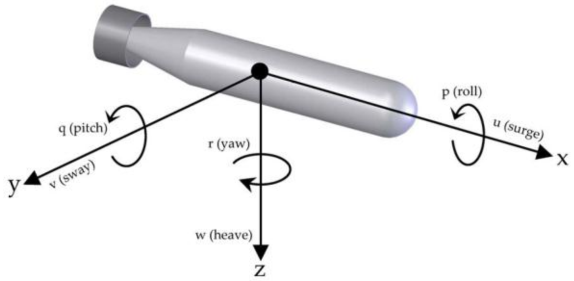

Fig. 1 AUV's kinematic variables

Attitude representation of the kinematic AUV model in the global reference frame is defined using Euler angles. This work considers the kinematic equation which is written as,

$$\dot{\eta} = J(\eta)\nu = \begin{bmatrix} R(\eta) & 0 \\ 0 & T(\eta) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} \tag{1}$$

where $R(\eta),\ T(\eta) \in \mathbb{R}^{3\times 3}$ and $\eta,\ \nu \in \mathbb{R}^{6\times 1}$,

$$\begin{array}{lllll} \nu & = & [\nu_1, \nu_2]^{\mathsf{T}} & = & [u, v, w, p, q, r]^{\mathsf{T}} \\ \eta & = & [\eta_1, \eta_2]^{\mathsf{T}} & = & [x, y, z, \phi, \theta, \psi]^{\mathsf{T}} \end{array} \tag{2}$$

3. Sliding mode controller

In the SMC, the sliding surface is designed so that the surface tends to and converges to zero when it satisfies the Lyapunov stability criterion.

3.1 Sliding surface

The problem of tracking is equivalent to that of remaining the trajectories on the surface for $t > 0$. Define the tracking error,

$$\tilde{x} = x - x_d \tag{3}$$

where x and x_d are state vector and desired state vector, respectively. Such that a time-varying sliding surface [4], [6] is given,

$$\sigma = h^{\mathsf{T}}\tilde{x} = h^{\mathsf{T}}(x - x_d) \tag{4}$$

where h is the right eigenvector.

The control inputs can be regarded as that for the nominal plant and for the uncertainty of model parameter. The control law of sliding mode is generally given,

$$\bar{u} = -kx - K_\sigma \mathrm{sgn}(\sigma) \tag{5}$$

where K_σ is a constant, corresponding to the maximum value of the controller input and the signum function is,

$$\mathrm{sgn}(\sigma) = \begin{cases} -1, & \text{if } \sigma < 0; \\ 0, & \text{if } \sigma = 0; \\ 1, & \text{if } \sigma > 0. \end{cases} \tag{6}$$

3.2 Chattering effects

A signum function causes a switching action known as a chattering effect. Thus the switching action may cause the system response to oscillate about the zero sliding surface in high frequency mode. This effect can cause wear on the actuators. To reduce the effect of chattering, a thin boundary layer of thickness around the switching surface is proposed in [5]. The control law with a modification is,

$$u = -k^{\mathsf{T}}x - K_\sigma \mathrm{sat}\left(\frac{\sigma}{\Phi}\right) \tag{7}$$

4. Decoupled Subsystems of an AUV

The control of six degrees of freedom AUV may be important for the operation, particularly in the motion transition. It is however not the primary focus in this work due to its complexity. The general six degrees of freedom AUV can be divided into lightly interacting or non-interacting subsystems. Therefore the computational time in determining each control element will be relatively short. A controller that is decoupled into two subsystems of heading and depth (see Fig. 2) is commonly found in [7], [8]. In the following sections, two subsystems based on the sliding mode are detailed.

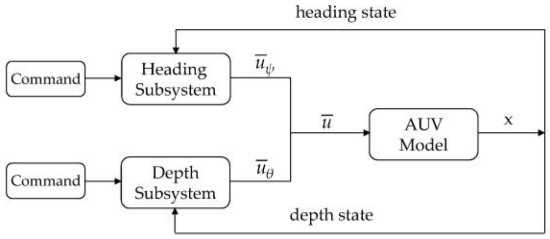

Fig. 2 Heading and depth subsystems

4.1 Heading subsystem

The heading subsystem provides the steering action to the AUV. The control input commands deflection of rudder. The heading subsystem comprises the sway velocity v, the yaw rate r, the heading angle ψ and the rudder deflection u_ψ. By assuming an AUV moving forward with constant speed u_0 = 1.3 m/s, the linearised equation of motion for heading subsystem is given in Eq. (8).

4.2 Depth subsystem

The depth subsystem presents the depth motion of the AUV. The control input commands deflection of sternplanes or bowplanes. The depth subsystem comprises the heave velocity w, the pitch angular velocity q, the pitch angle θ , the depth z and the sternplane deflection u_θ. By assuming an AUV moving forward with constant speed u_0, the linearised equation of motion in heave and pitch is therefore given in Eq. (9).

5. Simulation results

In this section, simulation results are implemented by using SMC controllers as described in section 4. Defining the parameters of a torpedo shaped AUV [54], the simulation of subsystems are shown. In the heading control, the desired heading angle is ψ_d = 60°. Fig. 4 and 5 depict the results of plots for heading control without disturbance and with disturbance, respectively. The disturbance using a random noise is added into each state. In the depth control, the desired depth is set as z_d = 10 meters, desired pitch angle ad pitch rate as zero. Fig. 6 and 7 show the plots for the depth control using a sliding mode controller to the system with and without disturbances, respectively. From simulation, sliding mode controller is able to provide accurate control for system without disturbance and also manage the heading for system with disturbance, only with small steady state errors.

$$\begin{bmatrix} m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} & 0 \\ mx_g - N_{\dot{v}} & I_{zz} - N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} Y_v & Y_r - mu_0 & 0 \\ N_v & N_r - mx_g u_0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} Y_\delta \\ N_\delta \\ 0 \end{bmatrix} u_\psi \tag{8}$$

$$\begin{bmatrix} m - Z_{\dot{w}} & -mx_g - Z_{\dot{q}} & 0 & 0 \\ -mx_g - M_{\dot{w}} & I_{yy} - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} Z_w & Z_q - mu_0 & 0 & 0 \\ M_w & M_q - mx_g u_0 & -z_b W & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -u_0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} + \begin{bmatrix} Z_\delta \\ M_\delta \\ 0 \\ 0 \end{bmatrix} u_\theta \tag{9}$$

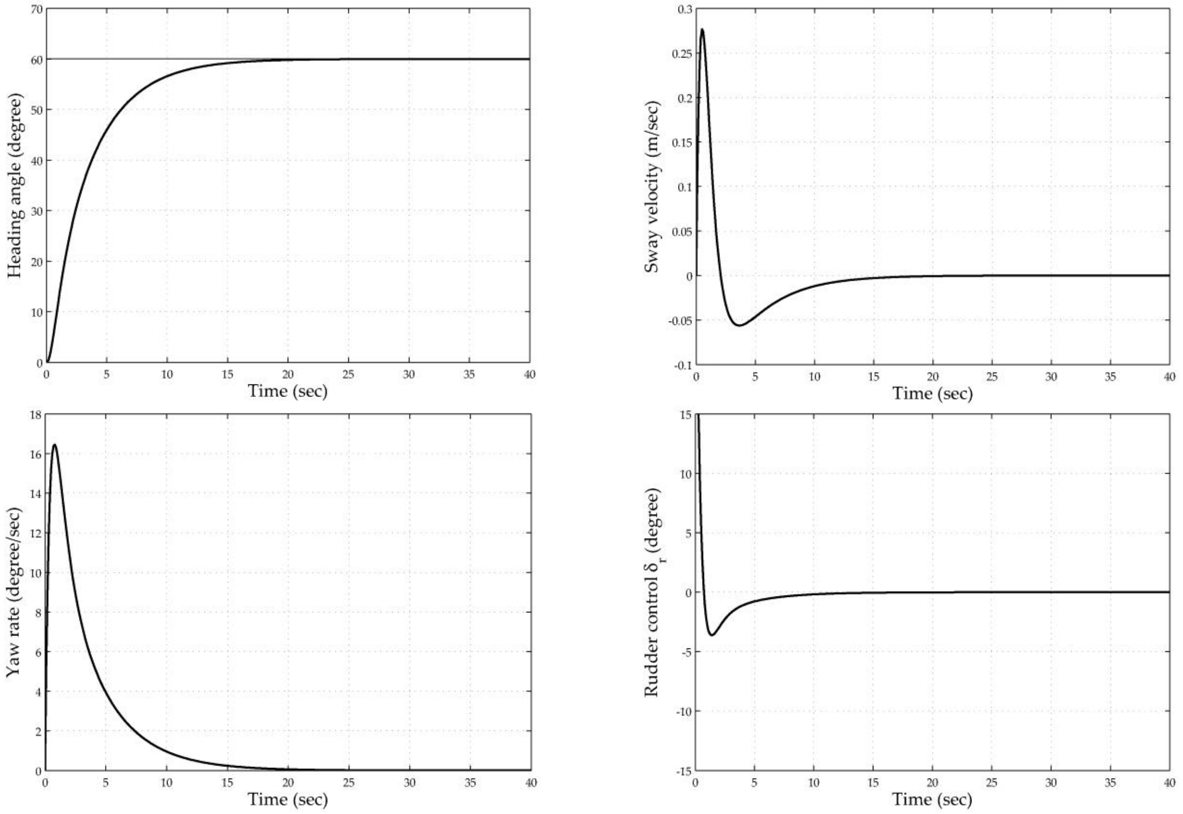

Fig. 3 Heading control without disturbance

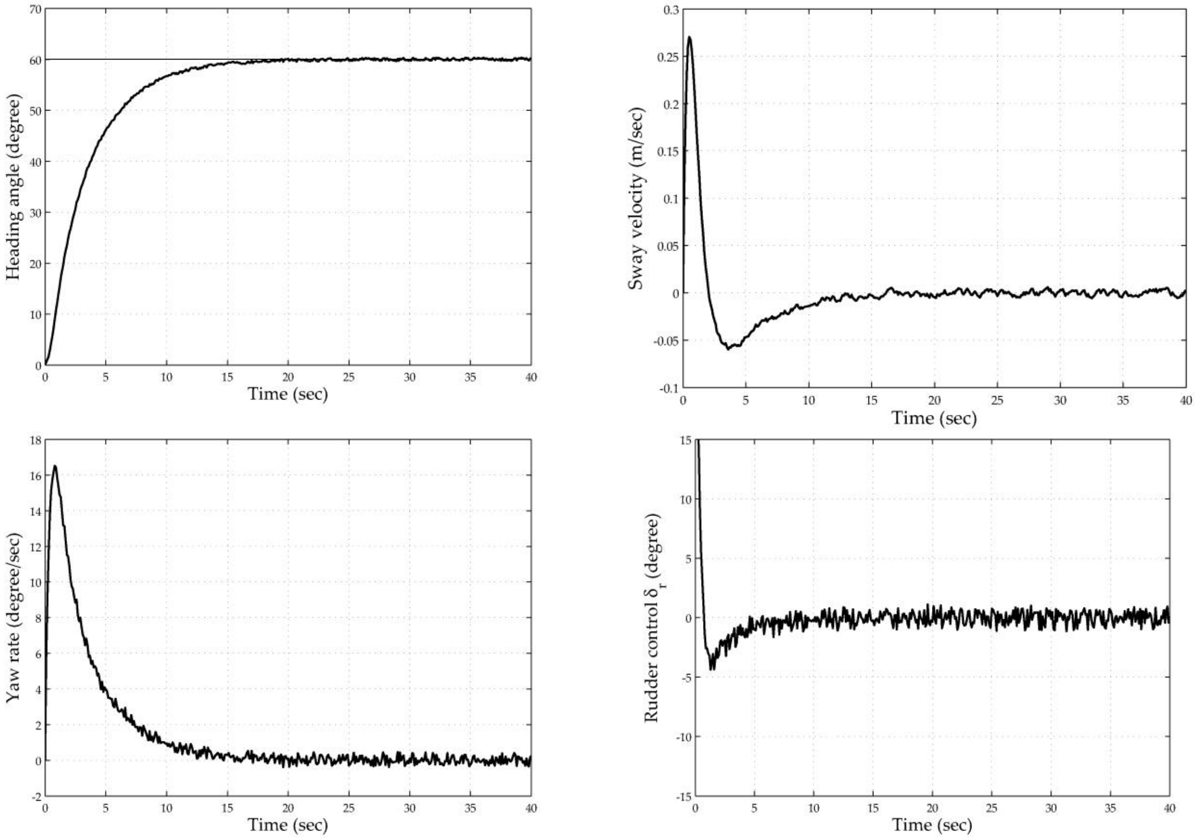

Fig. 4 Heading control with disturbance. The values of Root Mean Square (RMS) for the heading and rudder control are [55.9469, 2.6042].

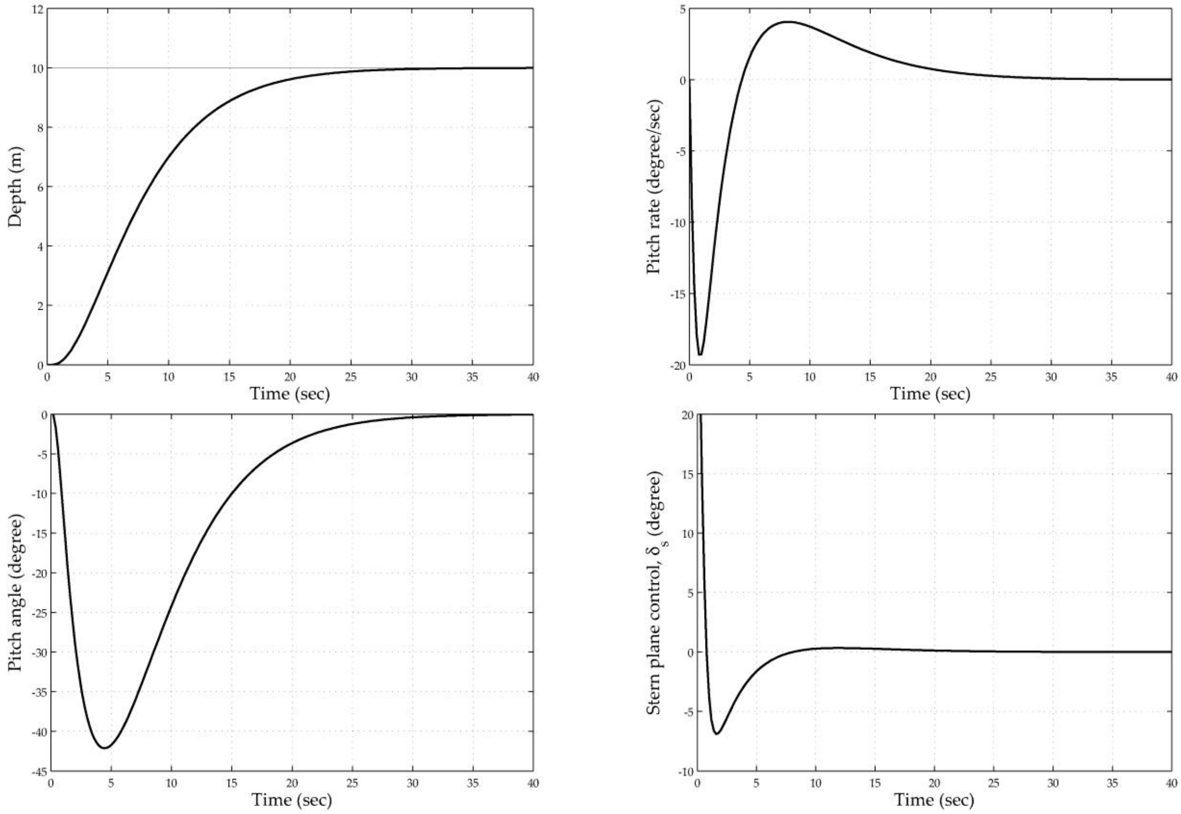

Fig. 5 Depth control without disturbance

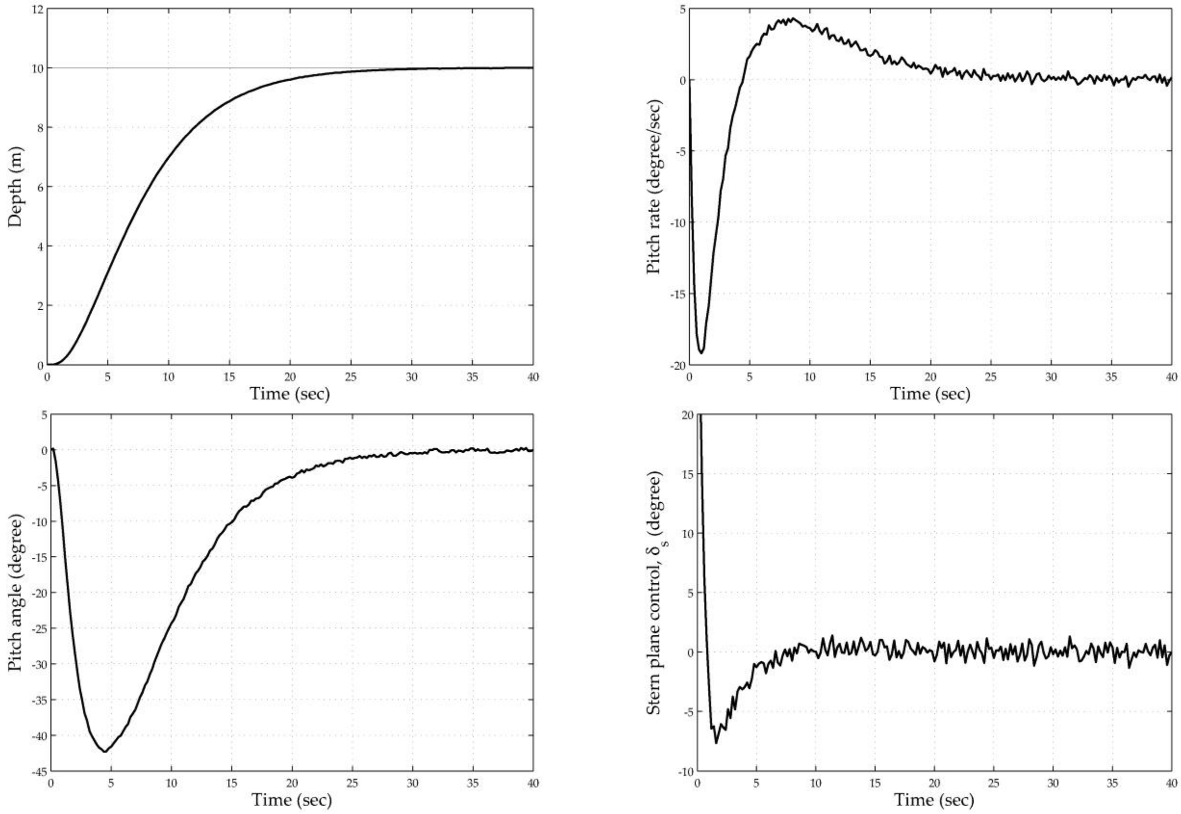

Fig. 6 Depth control with disturbance. The values of RMS for the depth and sternplane control are [8.4759, 3.7031].

6. Conclusion

The development of a robust controller for an AUV’s subsystems is presented in this paper. The sliding mode controller has been introduced to provide system’s stability. It guarantees that an AUV is able to converge to a desired heading and depth with constant speed as demonstrated in the simulation. From simulation, a sliding mode controller is able to provide accurate control for subsystems, which gives satisfactory results.

7. References

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