

# Sliding Mode Control of Autonomous Underwater Vehicles

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**Abstract**—This paper describes a sliding mode controller for autonomous underwater vehicles (AUVs). The dynamic of AUV model is highly nonlinear because of many factors, such as hydrodynamic drag, damping, and lift forces, Coriolis and centripetal forces, gravity and buoyancy forces, as well as forces from thruster. To address these difficulties, a nonlinear sliding mode controller is designed to approximate the nonlinear dynamics of AUV and improve trajectory tracking. Moreover, the proposed controller can profoundly attenuate the effects of uncertainties and external disturbances in the closed-loop system. Using the Lyapunov theory the boundedness of AUV tracking errors and the stability of the proposed control system are also guaranteed. Numerical simulation studies of an AUV are included to illustrate the effectiveness of the presented approach.

**Keywords**—Lyapunov stability, autonomous underwater vehicle (AUV), sliding mode controller, electronics engineering.

## I. INTRODUCTION

IN the last three decades, autonomous underwater vehicles (AUVs) have become a research topic in the field of robotics because of the commercial and military potential and the technological challenge in developing them [1], [2]. Because of the non-linearity and the unpredictable operating environment of the AUVs, many design parameters must be considered during the design of AUVs control system. Indeed, the high frequency oscillating movement can seriously affect the performance of sensors, especially optical and acoustical sensors.

In brief, the main factors that make the control of AUVs difficult are: (1) the highly nonlinear, time-varying dynamic behavior of the AUVs; (2) uncertainties in hydrodynamic coefficients; (3) disturbances by ocean currents [3]. To remedy these aforementioned problems and enhance the AUVs performance along with strengthen robustness, adaptability and autonomy, it is necessary that the motion control system has the ability of learning and self-adaptation.

Several control approaches have been applied, such as sliding control [4], [5], nonlinear control [6], adaptive control [7], and fuzzy control [8], [9].

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The capability of neural networks for function approximation, classification, and their ability to deal with uncertainties and parameter variations make them a valuable choice for use in control of the AUVs [10], [11]. Liang et al. proposed a novel motion controller based on parallel neural network for the AUV, which can enhance the training speed of neural network [12]. It is shown that parallel neural network can be utilized for the establishment of highly reliable and robust control systems for the AUV. In [13], a neural network adaptive controller with a linearly parameterized neural network (LPNN) is introduced to approximate the nonlinear uncertainties of AUV dynamics. In this approach, the basis function vector of LPNN is built according to the physical properties of the AUV. Moreover, a sliding mode control structure is used to remedy the effects of network reconstruction errors and disturbances in AUV dynamics. The method in [14] developed a stable neural network controller to approximate the nonlinear effect of AUV's dynamic and provide improved performances. Then, Using the Lyapunov approach, the uniformly ultimately bounded (UUB) stability of the proposed controller is demonstrated.

In this paper, a novel sliding mode control structure for autonomous underwater vehicles (AUVs) is proposed. In this case, a stable sliding mode controller is developed to approximate unknown nonlinear functions in the AUV dynamics, hence overcoming some limitation of conventional controllers such as PID/PD controller and improve AUV tracking performance. This controller can easily reject disturbance and robust to dynamic exchange in AUV dynamics during movement in unpredictable operating environment.

The rest of this paper organized as follows. Section II describes the uncertain nonlinear model of the AUV's dynamic. In Section III we describe the structure of sliding mode controller. Section IV gives the simulation results and finally, Section V draws conclusions and sums up the whole paper.

## II. AUV DYNAMICS MODEL

The dynamic model of an AUV is introduced in this section. This AUV model is useful for both formulating control algorithms and simulations. The AUV dynamic model, which presented in this section, is based on the underwater robotic models proposed by Fossen [15] and Yuh [16].

The dynamic model, which is derived from the Newton-Euler motion equation, is given by,

$$M\dot{v} + C(v)v + D(v)v + G = \tau \quad (1)$$

where  $M$  is a mass and inertia matrices,  $C(v)$  is a Coriolis and centripetal terms matrices,  $D(v)$  is a hydrodynamic damping matrices,  $G$  is the gravitational and buoyancy vector,  $\tau$  is the external force and torque input vector, and  $v$  is the velocity state vector. Note that in (1), environmental forces are not taken into account.

#### A. Mass and Inertia Matrices

$M \in \mathfrak{R}^{6 \times 6}$  consists of both a rigid body mass and inertia,  $M_{RB} \in \mathfrak{R}^{6 \times 6}$ , and a hydrodynamic added mass,  $M_A \in \mathfrak{R}^{6 \times 6}$ . given by,

$$M = M_{RB} + M_A \quad (2)$$

#### B. Coriolis and Centripetal Matrices

$C(v) \in \mathfrak{R}^{6 \times 6}$ , like the mass matrices consists of two matrices,  $C_{RB}(v) \in \mathfrak{R}^{6 \times 6}$  and  $C_A(v) \in \mathfrak{R}^{6 \times 6}$ , which can be expressed as,

$$C(v) = C_{RB}(v) + C_A(v) \quad (3)$$

where  $C_{RB}(v)$  is the rigid body Coriolis and centripetal matrices induced by  $M_{RB}$ , while  $C_A(v)$  is a Coriolis-like matrices induced by  $M_A$ .

#### C. Hydrodynamic Damping Matrices

The hydrodynamic damping matrices represents the drag and lift forces acting on a moving underwater vehicle. Nevertheless, for a low-speed underwater vehicle, the lift forces are negligible when compared to the drag forces. These drag forces can be separated into two different terms composed of a linear and quadratic term [17], given by,

$$D(v) = \text{diag}\{D_L + D_Q|v|\} \quad (4)$$

where  $D_L \in \mathfrak{R}^{6 \times 6}$  is the linear damping term, while  $D_Q \in \mathfrak{R}^{6 \times 6}$  is the quadratic damping term.

#### D. Gravitational and Buoyancy Vector

The gravitational and buoyancy vector,  $G \in \mathfrak{R}^{6 \times 1}$ , is defined as,

$$G = \begin{bmatrix} f_B + f_C \\ r_B \times f_B + r_C \times f_C \end{bmatrix} \quad (5)$$

where  $f_B$  and  $f_C$  are the buoyant force vector and the gravitational force vector, respectively. Moreover,  $r_B$  is the centre of buoyancy and  $r_C$  is the centre of gravity or mass in frame  $\{B\}$ .

#### E. Forces and Torque Vector

The external force and torque vector produced by the thrusters can be expressed as,

$$\tau = LU \quad (6)$$

where  $L$  is a mapping matrices and  $U$  is a thrust vector.  $U$  is the vector of thrusts produced by the vehicle's thrusters,

$$U = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_n \end{bmatrix} \quad (7)$$

The number of thrust values in  $U$  is related to the number of thrusters on the vehicle. The mapping matrix  $L$  is essentially a  $6 \times n$  matrix that uses  $U$  to find the overall forces and moments acting on the vehicle.

### III. SLIDING MODE CONTROL STRUCTURE

The AUV dynamic in (1) can be rewritten as

$$M\ddot{q} + C(\dot{q})\dot{q} + D(\dot{q})\dot{q} + G + \tau_d = \tau \quad (8)$$

where  $M$ ,  $C(v)$ ,  $D(v)$  and  $G$  are introduced in pervious section. Moreover,  $q$  is the configuration and  $\tau_d$  represents environmental forces and/or disturbances [18]. To make the AUV follow a prescribed desired trajectory  $q_d(t)$ , we define the tracking error  $e(t)$  and filtered tracking error  $r(t)$  by

$$e = q_d - q, \quad r = \dot{e} + \Lambda e \quad (9)$$

with  $\Lambda > 0$  a positive definite design parameter matrices. The AUV dynamics are expressed in terms of the filtered error as

$$M\dot{r} = -Cr + f(x) + \tau_d - \tau \quad (10)$$

where the unknown nonlinear function of AUV dynamic is given by

$$f(x) = M(q)(\ddot{q}_d + \Lambda\dot{e}) + C(\dot{q})(\dot{q}_d + \Lambda e) + D(\dot{q})\dot{q} + G \quad (11)$$

One may define  $x \equiv [e^T, \dot{e}^T, \dot{q}_d^T, \ddot{q}_d^T]^T$ .

The AUV's dynamics like any other Lagrangian system has some important properties. These properties simplify the AUV's dynamics significantly. Moreover, these properties are highly useful in robust control approaches and as follows:

**P1:** The inertia matrix  $M(q)$  is symmetric, positive definite and bounded so that  $\mu_1 I \leq M(q) \leq \mu_2 I$  for all  $q(t)$ .

**P2:** The coriolis/centripetal vector  $C(q, \dot{q})\dot{q}$  is quadratic in  $\dot{q}$  and  $C$  is bounded so that  $\|C\| \leq c_B \|\dot{q}\|$ .

**P3:** The coriolis/centripetal matrix can always be selected so that the matrix  $S(q, \dot{q}) = \dot{M}(q) - 2C(q, \dot{q})$  is skew symmetric. Therefore,  $x^T Sx = 0$  for all vectors  $x$ .

A general robust controller structure is based on

$$\tau = \hat{f} + K_v r - v(t) \quad (12)$$

with  $\hat{f}$  an estimate of  $f(x)$ ,  $K_v r = K_v \dot{e} + K_v \Lambda e$  an outer PD tracking loop, and  $v(t)$  an auxiliary signal as

$$v(t) = -(F(x) + \eta) \text{sgn}(r) \quad (13)$$

where  $\text{sgn}(\cdot)$  is the sign function and  $F(x)$  is a known function which can be computed using the boundedness property of AUV's dynamics. This term is used to maintain the robustness in the face of external forces, disturbances and modeling error [10].  $\eta$  is a design parameter and can be selected as a small value. Employing this controller, the closed-loop error dynamics are

$$M\dot{r} = -Cr - K_v r + \tilde{f} + \tau_d + v(t) \quad (14)$$

where the function approximation error is defined as

$$\tilde{f} = f - \hat{f} \quad (15)$$

so that  $\|\tilde{f}\| \leq F(x)$  and  $\|\cdot\|_F$  is the Frobenius norm.

To prove the stability of the introduced controller, some assumptions are needed. These assumptions are true in every practical situation.

**Assumption 1:**

The desired trajectory is bounded so that

$$\begin{bmatrix} \|q_d(t)\| \\ \|\dot{q}_d(t)\| \\ \|\ddot{q}_d(t)\| \end{bmatrix} < q_B \quad (16)$$

with  $q_B$  a known scalar bound.

**Theorem:**

Let the desired trajectory  $q_d(t)$  be bounded by  $q_B$  as in Assumption 1 and the disturbance  $\tau_d$  is zero. Then, using the tracking error norm  $\|r\|$  is eventually bounded to the neighborhood of  $\varepsilon$ .

The proof of this theorem can be found in [10].

#### IV. SIMULATION

The simulation results obtained from the implementation of proposed sliding mode controller on a low-speed AUV named Mako [19], which has high symmetry, modularity and stability. The robust controller parameters chosen for the simulation were as follows,

$$\eta = 0.1, K_v = 40 \times \text{diag}(8, 1, 15, 1, 1, 0.8)$$

$$\Lambda = 5 \times \text{diag}(2.5, 0.5, 1.5, 5, 5, 5)$$

The simulation is done using Simulink in MATLAB. The response of the simulated controller for linear velocities  $u$ ,  $v$  and  $w$  representing the surge, sway and heave, respectively, are shown in Fig. 1. The angular velocities roll, pitch and yaw about the  $x$ ,  $y$  and  $z$ -axes, respectively, are shown in Fig. 2.

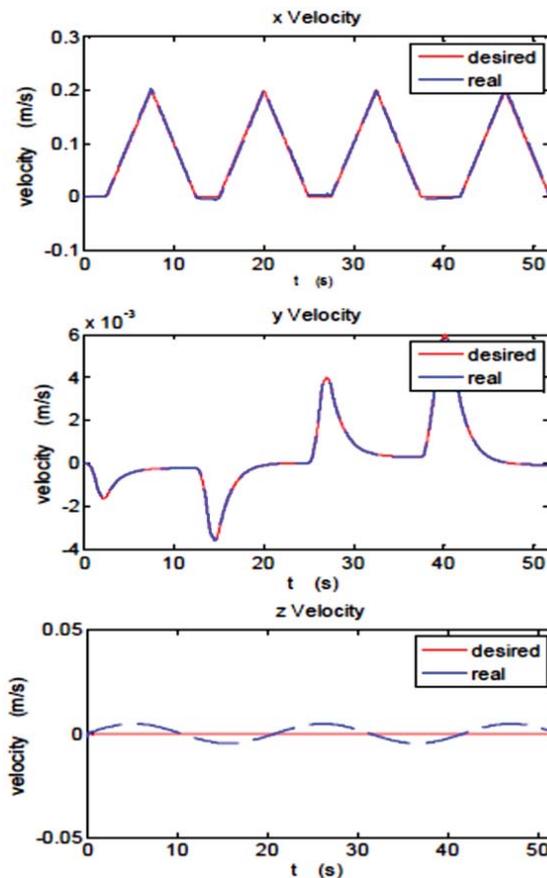


Fig. 1 Simulation results for the linear velocities

The control signals of sliding mode controller are shown in Fig. 3. The linear and angular velocities tracking response is superb and control signals are bounded. Moreover, no initial training or learning phase was needed.

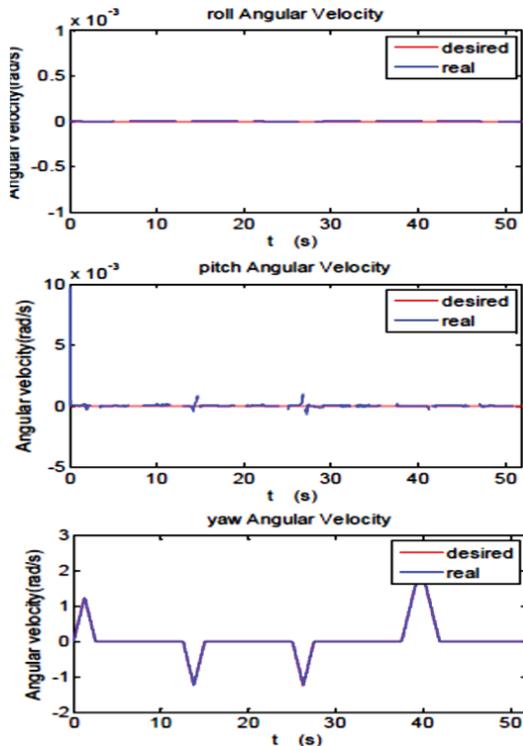


Fig. 2 Simulation results for the angular velocities

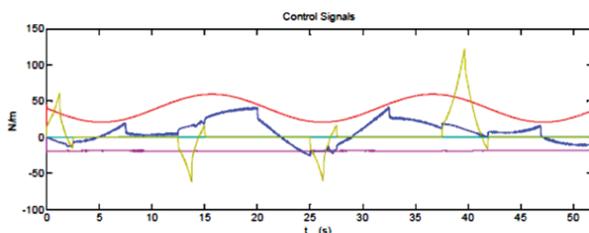


Fig. 3 The control signals of sliding mode controller

## V. CONCLUSION

This paper introduced a novel stable sliding mode controller for application of an autonomous underwater vehicle (AUV). The proposed controller improved velocities tracking performance of the AUV, while guarantee boundedness of both tracking error. Therefore, guarantee accurate and dynamic following of prescribed trajectories. The proposed controller has superior tracking performance than that of conventional controllers. Numerical simulation results in MATLAB showed the validity and effectiveness of the proposed controller.

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