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Sliding Mode Control under Wave Disturbances for an AUV Using Nonlinear Observer Method

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***Abstract*—This paper mainly presents that the influence from high-frequency wave disturbances to the motion of the AUV when it operates in shallow water. To solve the issue above, a nonlinear observer is proposed to derive the disturbance information of wave by estimating the shallow water wave's velocities and AUV's relative velocities from position and attitude measurement. With the observer estimates, the position errors in X, Y, Z directions are obtained by the velocity errors in surge, sway and heave. Meanwhile, a sliding mode controller is designed to make AUV keep stability while moving in the three dimensional space. Simulation results demonstrated that the proposed method is effective to eliminate wave disturbance and performs well.**

Keywords—AUV; sliding mode controller; nonlinear observer

I. Introduction

As Autonomous Underwater Vehicle (AUV) has become one of the most significant instruments for large-area oceanic researching and developing, the AUV's position information is crucial to its safety and fulfillments of missions [1]. However, due to the fact that the signal of Global Positioning System (GPS) attenuates is extremely absorbed by the water, GPS can't provide position information for AUV while it is sailing underwater. So the vehicle has to sail near the surface some time in order to receive the signal from GPS for calibration of the navigation system. In addition, the communication between the AUV and mother ship also require the AUV sailing in the shallow water. When AUV is operating in this condition, the wave is the main disturbance [2-3].

Most previous researches have focused on AUV's motion in deep water where the influence of wave disturbance can be neglected [4]. In shallow water, the wave disturbance has to be taken into account due to its significant effect on AUV motion. Since it is not energy efficient to counteract high frequency oscillatory wave disturbances, it is critical to eliminate the wave disturbances from the feedback loop to avoid wear and tear on thrusters[5]. This is achieved by using wave filtering method, which separates position measurement into low-frequency and wave frequency position estimates. The control action of the thrusters is derived using the estimated states of the low-frequency model [6].

Therefore, more advanced controllers are currently being investigated so that the tracking objective can be achieved in a satisfactory manner with a reduced number of actuators. For example, Yoerger and Slotine proposed and successfully used a sliding mode controller for an ROV maneuvering around large objects at very slow speed. Fossen and Strand proposed a nonlinear passive observer for dynamic positioning control of surface ships with adaptive filtering. Lee propose a discrete-time quasi-sliding mode controller wihich was used for controlling the depth of an AUV, and the control algorithm was confirmed to be effective with model uncertainties and large sampling periods. Xiong provides a robust H_∞ filter for AUV's heading control system, which was designed to enhance dynamic quality of the heading control[7]. In [8], a robust controller for heading control of AUV was designed based on closed-loop gain shaping algorithm, however its performance was not so good when the velocity was changed.

In this paper, we propose a sliding mode controller with a nonlinear observer which stabilizes the AUV moving in underwater space. The control objective is to make the vehicle, with the wave disturbance, sail from one point to another point in the configuration horizontal plane and from certain depth to shallow water where vehicle is planned to sail at. The main approach adopted in the control strategy is to assign the error which is achieved from the measured data by using the nonlinear observer to the sliding mode controller, then the modified is made by the controller. Sliding mode control is a popular method and has been successfully applied to AUVs. It can give a good system performance which includes insensitivity to parameter variations and good rejection of disturbances.

This paper is organized as follows. In section II, the dynamic model of the AUV and wave model are introduced. Section III shows the nonlinear observer and the sliding mode controller Section IV illustrates the results of the sliding mode controller with simulation. Finally, in section V, some results and advices are concluded.

II. Mathematical model

In this section, a brief introduction of BSA-AUV is presented at first. Then the kinematic model of AUV is introduced. At last, the wave model is presented so that disturbance can be simulated.

A. 6-DOF Model of AUV

The kinematic model of AUV in shallow water can be described by the following equations [9]:

$$\dot{\eta}_1 = J_1(\eta_2)v_1 \tag{1}$$

$$\dot{\eta}_2 = J_2(\eta_2)v_2 \tag{2}$$

In order to simplify the calculation in the following parts, the equations are changed as below:

$$\dot{\eta}_1 = J_1(\eta_2)v_{1r} + U_f \tag{3}$$

$$\dot{\eta}_2 = J_2(\eta_2)v_2 \tag{4}$$

where $\eta_1 = [x \;\; y \;\; z]^{\mathrm{T}} \in \mathbf{R}^3$ and $\eta_2 = [\varphi \;\; \theta \;\; \psi] \in \mathbf{R}^3$ respectively describe the state vectors of the vehicle position and attitude in the earth-fixed frame; $v_{1r} = [u_{1r} \;\; v_{1r} \;\; w_{1r}]^{\mathrm{T}} \in \mathbf{R}^3$ and $v_2 = [p \;\; q \;\; r] \in \mathbf{R}^3$ denote the vectors of linear velocities and angular velocities in the body-fixed frame; U_f means the wave velocity vector in the earth-fixed frame, and $J_1(\eta_2), J_2(\eta_2)$ are kinematic transformation matrices.

$$J_1(\eta_2) = \begin{bmatrix} \mathrm{c}\psi\mathrm{c}\theta & -\mathrm{s}\psi\mathrm{c}\varphi + \mathrm{s}\varphi\mathrm{s}\theta\mathrm{c}\psi & \mathrm{s}\psi\mathrm{s}\theta + \mathrm{s}\theta\mathrm{c}\psi\mathrm{c}\varphi \\ \mathrm{s}\psi\mathrm{c}\theta & \mathrm{c}\psi\mathrm{c}\varphi + \mathrm{s}\varphi\mathrm{s}\theta\mathrm{s}\psi & -\mathrm{c}\psi\mathrm{s}\varphi + \mathrm{s}\theta\mathrm{s}\psi\mathrm{c}\varphi \\ -\mathrm{s}\theta & \mathrm{s}\varphi\mathrm{c}\theta & \mathrm{c}\varphi\mathrm{c}\theta \end{bmatrix} \tag{5}$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & \mathrm{s}\varphi\,\mathrm{t}\theta & \mathrm{c}\varphi\,\mathrm{t}\theta \\ 0 & \mathrm{c}\varphi & -\mathrm{s}\varphi \\ 0 & \mathrm{s}\varphi/\mathrm{c}\theta & \mathrm{c}\varphi/\mathrm{c}\theta \end{bmatrix} \tag{6}$$

where $s\cdot = \sin(\cdot)$, $c\cdot = \cos(\cdot)$ and $t\cdot = \tan(\cdot)$.

The dynamic model of AUV is denoted in the body-fixed frame as follows:

$$M\dot{v}_r + C(v)v_r + D(v)v_r + g(\eta) = \tau_1 + \tau_2 \tag{7}$$

where $v_r \in \mathbf{R}^6$ represents the state vector of AUV; $M \in \mathbf{R}^{6\times 6}$ consists of inertia matrix and add mass matrix; $C(v) \in \mathbf{R}^{6\times 6}$ is the Coriolis and centripetal matrix; $D(v) \in \mathbf{R}^{6\times 6}$ is the linear and quadratic damping matrix; $g(\eta) \in \mathbf{R}^6$ is a vector of generalized gravitational and buoyancy forces; $\tau_1, \tau_2 \in \mathbf{R}^{3\times 3}$ represent the forces and moments acting on the vehicle.

In order to simplify the model and calculation, Eq.7 can be rewritten as following:

$$\dot{v}_r = M^{-1}(F_1 + F_2) \tag{8}$$

where $F_1 = -C(v)v - D(v)v + g(\eta)$; F_2 is a composition of forces from all the actuators), including propellers, rudders and so on. As the hydrodynamic coefficients, barycenter and moment of inertia have been measured. The current velocity has been known. M and F_1 are both known.

B. Wave Model

The main disturbance to AUVs in shallow water is the first-order wave disturbance.

Assumption 1: The wave has no influence on the angular velocities of vehicle.

In the paper, the first-order wave disturbance is described as a wave velocity model in the following equation:

$$\dot{\xi} = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \begin{bmatrix} 0 & I \\ \Omega_{21} & \Omega_{22} \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \Sigma_2 \end{bmatrix} n_1 \tag{9}$$

$$U_f = \begin{bmatrix} 0 & I \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \tag{10}$$

$$\Omega_{21} = -\begin{bmatrix} \omega_{o1}^2 & & \\ & \omega_{o2}^2 & \\ & & \omega_{o3}^2 \end{bmatrix} \tag{11}$$

$$\Omega_{22} = -\begin{bmatrix} 2\zeta_1\omega_{o1} & & \\ & 2\zeta_2\omega_{o2} & \\ & & 2\zeta_3\omega_{o3} \end{bmatrix} \tag{12}$$

where $\xi_1, \xi_2 \in \mathbf{R}^3$ are respectively the water particle position and velocity vectors; Ω_{21}, Ω_{22} are the dominating wave frequency; Σ_2 is a parameter related to wave intensity.

III. NONLINEAR OBSERVER AND SLIDING MODE CONTROLLER

A. Nonlinear Observer

The AUV's model used in shallow water can be expressed in the new coordinate frame as follows:

$$\dot{\eta}_1 = J_1(\eta_2)v_{1r} + U_f \tag{13}$$

$$\dot{\xi} = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \begin{bmatrix} 0 & I \\ \Omega_{21} & \Omega_{22} \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \tag{14}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} \tag{15}$$

Then they are changed as following:

$$\dot{\eta}_0 = A_0\eta_0 + B_0 J_1(\eta_2)v_{1r} \tag{16}$$

$$y_1 = C_0\eta_0 \tag{17}$$

where $\eta_0 = \begin{bmatrix} \xi_1^T & \xi_2^T & \eta_1^T \end{bmatrix}^T$; $A_0 = \begin{bmatrix} 0 & I & 0 \\ \Omega_{21} & \Omega_{22} & 0 \\ 0 & I & 0 \end{bmatrix}$; $B_0 = \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix}$; $C_0 = \begin{bmatrix} 0 & 0 & I \end{bmatrix}$

As the wave just influences the translational motion, and the attitude angles and rotational velocity can be measured accurately by using the gyro compass and inertial measurement unit, the motivation of nonlinear observer design is to estimate the wave velocity and its relative speed with AUV. When the dominating wave frequency is known, the observer has the property of a notch filter in the frequency range of the wave disturbances. If the wave frequency is unknown or slowly time varying, an adaptive nonlinear observer could be designed with global asymptotical stability.

The observer for dynamics is proposed as

$$\dot{\hat{\eta}}_0 = A_0\hat{\eta}_0 + B_0 J_1(\eta_2)v_{1r} + H\tilde{y}_1 \tag{18}$$

$$\hat{y}_1 = C_0\hat{\eta}_0 \tag{19}$$

The nonlinear observer adopted in the paper is modified by the formulas above. Then the observer can be presented as:

$$\dot{\tilde{\eta}}_0 = (A_0 - HC_0)\tilde{\eta}_0 + B_0 J_1(\eta_2)v_{1r} \tag{20}$$

$$\tilde{y}_1 = H_4 C_0\tilde{\eta}_0 \tag{21}$$

where $\tilde{\eta}_0 = \eta_0 - \hat{\eta}_0 = \begin{bmatrix} \tilde{\xi}_1 & \tilde{\xi}_2 & \tilde{\eta}_1 \end{bmatrix}$. From the results of observer, the velocity errors $\tilde{\eta}_1 = \begin{bmatrix} \tilde{\eta}_{1u} & \tilde{\eta}_{1v} & \tilde{\eta}_{1w} \end{bmatrix}$ comprised by $\tilde{\eta}_0$ can be obtained.

B. Sliding Mode Controller

Sliding mode variable structure control, which is also called sliding mode control (SMC) for short, is widely applied in nonlinear control for its robustness to parameters uncertainty and mode perturbations. This control system is easy to design and comes true. And the design parameters are convenient to define and adjust.

According to $\tilde{\eta}_0$, the velocity errors in surge, sway and heave can be calculated. Three functions respectively in surge, sway and heave are designed with $\tilde{\eta}_1$, then Eq.22 is an example for the surge as following:

$$\dot{e}_1 = \begin{bmatrix} \dot{e}_{11} \\ \dot{e}_{12} \end{bmatrix} = \begin{bmatrix} \Delta\dot{X} \\ \dot{\tilde{\eta}}_{1u} \end{bmatrix} = \begin{bmatrix} e_{12} \\ \dot{u}_r - \dot{u}_e \end{bmatrix} \tag{22}$$

where ΔX is the position error of X axis; $\tilde{\eta}_{1u}$ is velocity error in surge; u_r, u_e are respectively real velocity and expected velocity in surge.

With the above all, Eq. 8 can be rewritten as following: (Eq.23 is an example for the surge and it is designed as i=1.)

$$\begin{aligned} \dot{u}_r &= M^{-1}(F_1 + F_2) \\ &= M^{-1}F_1 + M^{-1}F_2 \\ &= b_1 + u_1 \end{aligned} \tag{23}$$

where F_1, F_2 are all forces acting on the vehicle, including Coriolis and centripetal forces, thruster forces and so on; u_1 is the control input with i=1.

Combining Eq. 22 and Eq. 23, a related state equation can be presented as following:

$$\dot{e}_1 = Ae_1 + B + Cu \tag{24}$$

where $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$; $B = \begin{bmatrix} 0 \\ b_1 - \dot{u}_e \end{bmatrix}$; $C = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Choose the function of sliding mode control as:

$$s_i = C_{i1}e_{i1} + e_{i2} = 0, (i = 1,2,3) \tag{25}$$

where C_{i1} is obtained in the way of pole assignment method, and pole point is chosen as λ_i beforehand.

To improve the performance of dynamic, an asymptotic ratio strategy is selected and Eq.25 can be rewritten as Eq.26:

$$\dot{s}_i = C_{i1}\dot{e}_{i1} + \dot{e}_{i2} = -\varepsilon\,\mathrm{sgn}(s_i) - ks_i \tag{26}$$

where $i = 1, 2, 3$.

Now take $\dot{e}_{i2} = (b_i - \dot{u}_e) + u_i$ into the Eq.26, and a new function can be presented as:

$$u_i = -[b_i - \dot{u}_e] + [-\varepsilon \operatorname{sgn}(s_i) - ks_i] - C_{i1}e_{i2} \quad (27)$$

Then the control function can be described as:

$$u_i = -[b_i - \dot{u}_e] - C_{i1}\tilde{\eta}_{1k} + [-\varepsilon \operatorname{sgn}(s_i) - ks_i] \quad (28)$$

where $\dot{u}_e$ is replaced by $\dot{v}_e$, $\dot{w}_e$ with i=2, 3; $\tilde{\eta}_{1k}$ represents $\tilde{\eta}_{1u}, \tilde{\eta}_{1v}, \tilde{\eta}_{1w}$ with k=1, 2, 3.

IV. SIMULATION RESULT

Simulation tests are carried out based on the data from a validated model with all coefficients. The case is that the AUV operates from the depth of 4m to 1m, and then follows the path preplanned; both cases are under the wave disturbances. The results are shown in the following figures.

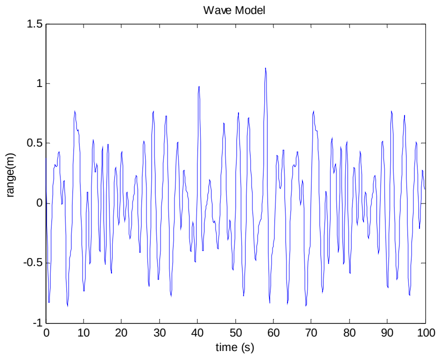

FIGURE I. THE WAVE MODEL

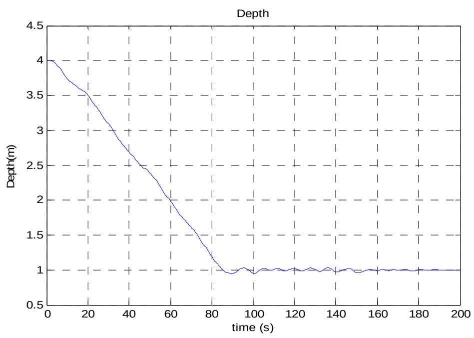

FIGURE II. THE DEPTH RESPONSE OF AUV

Figure I is the three class wave model which is based on the data from the result of simulation. The wave parameters are chosen from the table of the P-M wave class. The period of wave in surge, sway and heave is 5s.

Now AUV is made to take a mission, including float up from 4m to 1m, then AUV keeps this depth and drive as the desire path when it reaches this. When AUV is in the depth of 4m, the wave disturbances are much smaller than the disturbances in the 1m. So the surge in the 4m is much smaller than it in the 1m, and the sliding mode control designed keep AUV moving in a range we can receive. Figure III shows the pitch of AUV changes with the wave disturbances. With the control of sliding mode controller, the pitch is kept from -4 to 4 degree.

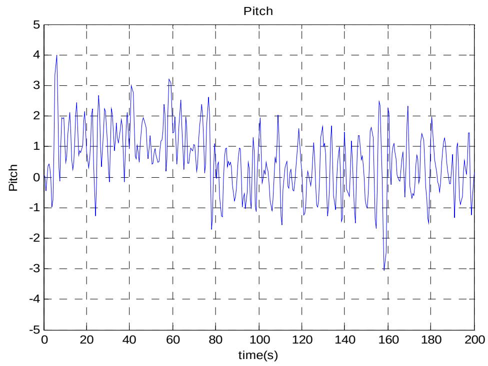

FIGURE III. THE PITH OF AUV

As shown in these figures, AUV can maintain its depth with great accuracy by counteracting the wave disturbances.

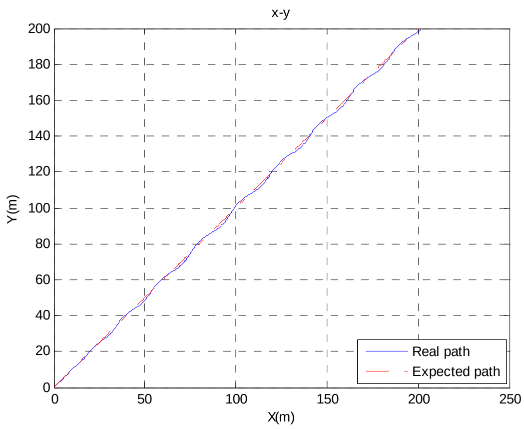

FIGURE IV. THE SIMULATION OF HORIZATION PLANE

Figure IV shows the actual and desired path in the horizontal plane. The desired path is a line from coordinate (0,0) to (200,200). With the nonlinear observer and sliding mode controller, the actual path of AUV is around the desired one in a little error which can be reached. This way can help AUV counteract the wave disturbances in horizontal plane.

V. CONCLUSION

AUVs have the potential for oceanographic survey capabilities in contrast with conventional ship. However, the wave has big influence on the AUVs which work in the shallow water under the wave disturbances. In order to achieve the accurate data and mission, AUVs have to forecast the wave disturbances and control the actuating mechanism to counteract the disturbances.

This paper proposes a methodology to develop a sliding mode controller with a nonlinear observer for AUV working in the shallow water under the wave disturbances. Firstly, we get an AUV model which includes Coriolis and centripetal forces and moments. Secondly, based on this model and the wave model, a nonlinear observer is developed to provide estimation of relative velocity of AUV and the wave velocity. Thirdly, a sliding mode controller is designed to control the rudders to follow the course and depth. Simulation results confirm that the synthesized observer-controller performs well with good stability and robustness.

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