Design of Sliding Mode Autopilot with Steady-state Error Elimination for Autonomous Underwater Vehicles

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Abstract— **Autonomous Underwater Vehicles (AUVs) have nonlinear and time-varying behaviour and unmodelled dynamics. This paper describes the design, development and evaluation of nonlinear sliding mode autopilot system for an AUV to control the speed, steering and depth of the nonlinear AUV. It has also been observed by some researchers that the sliding mode controller is unable to eliminate the steady-state error. A method of eliminating the steady-state error associated with the sliding mode controller has been proposed in this paper. In addition, performances of the sliding mode autopilot were evaluated by simulation on the nonlinear model of the AUV over a variety of operating conditions. The robustness of the control system was evaluated in the presence of disturbances and parameter uncertainties.**

I. Introduction

The increased desire to use AUVs for commercial and military applications has led to a great deal of research in this field over the last decade. The automatic control of such AUVs is very demanding as the dynamic model of the vehicle is highly nonlinear and coupled especially with the poorly known vehicle hydrodymanic coefficients. The vehicle also operates in an unknown environment with large wave and ocean current disturbances. The impact of the disturbances makes the design of the autopilot of the vehicle very difficult. The development of variable structure robust nonlinear control in the form of sliding modes has been reported by many researchers. Yoerger and Slotine [16], [17] have applied sliding mode controller design successfully in the control of underwater vehicles with a series of single-input single-output (SISO) continuous time controllers. The robustness of their control system, in the presence of parameter uncertainties, was demonstrated by computer simulation. Cristi, Papulias and Healey [2], Papoulias, Cristi, Marco and Healey [12] proposed an adaptive sliding mode controller for AUV based on the dominant linear model and the bounds of the nonlinear dynamic perturbations. Yoerger and Slotine [19] also used an adaptive sliding model control for underwater vehicles. Sliding model controllers have been implemented for the JASON vehicle at Woods Hole Oceanographic Institution by Yoerger, Newman and Slotine [18] and the MUST vehicle at Martin Marietta, Baltimore by Dougherty, Sherman, Woolweaver and Lovell [3] and Dougherty and Woolweaver [4]. Successful implementations have also been reported for the NPS AUV II at the Naval Postgraduate School, Monterey by Marco and Healey [10] and Healey and Lienard [7]. Marco and Healey have also applied sliding mode controllers to the control of NPS ARIES AUV at the Naval Postgraduate School [11].

In this paper, sliding mode autopilot is designed for the steering, diving and speed control functions for the REMUS vehicle (Remote Environmental Monitoring Units). The REMUS AUV was developed by von Alt and associates at the Oceanographic Systems Laboratory at the Woods Hole Oceanographic Institution [15]. The REMUS coefficients are given by Prestero [13]. A conventional PID depth controller designed based on the linearised depth plane model has been reported in [13].

It has been shown through a large numbers of experiements that sliding mode controllers have significant advantages to traditional controller designs based on linear control theory. As the sliding mode method can also reduce the inherent coupling between the vehicle response modes that exist in AUV vehicles, a separate design for the speed, diving and steering control systems has been adopted for the REMUS vehicle in this paper.

It has also been observed by some researchers that the sliding mode controller is unable to eliminate the steady-state error [9]. This paper provides a method of eliminating the steady-state error associated with the sliding mode controller. In addition, performances of the sliding mode controllers were evaluated by simulation on the nonlinear model of the AUV over a variety of operating conditions. The robustness of the control system was evaluated in the presence of disturbances and parameter uncertainties. The simulation results show that the nonlinear sliding mode control approach controls the speed, steering and depth of the AUV successfully.

II. Underwater Vehicle Modeling

Two coordinate systems are necessary for specifying the physical behaviour of underwater vehicles. These two coordinate systems are *world coordinate* and *body coordinate* [1]. The linear and angular velocities of a AUV are described by

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(u, v, w, p, q, r) in the body coordinate system. The position (x, y, z) and orientation (ϕ, θ, ψ) of a AUV are described with respect to the world coordinate frame [5]. The orientation of a AUV is described by defining the orientation of the body coordinate frame with respect to the world coordinate frame using Euler angles *roll* ϕ, *pitch* θ, and *yaw* ψ. The kinematic equation of motion describes the geometric relationships between motion in the body coordinate frame and motion in the world coordinate frame. The detail derivation can be found in [5] and [1].

The rigid-body equations of motion express the relationships that exist between the forces and moments acting on a rigid-body and its linear and angular velocities. The rigid-body equations are derived from Newtonian and Lagrangian mechanics. These equations can be expressed in vectorial form as:

$$\boldsymbol{M}_{RB}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau}_{RB} \tag{1}$$

where $\boldsymbol{\nu} = \left[u, v, w, p, q, r\right]^T$ is the body coordinated velocity vector and $\boldsymbol{\tau}_{RB}$ is the body coordinated vector of external forces and moments. $\boldsymbol{M}_{RB}$ is the inertia (or mass) matrix and $\boldsymbol{C}_{RB}$ is the coriolis-centripetal matrix [5],[1].

Three primary sources of external forces and moments that act on AUVs can be identified as hydrodynamic, environmental and control. The body coordinated vector of external forces and moments from Eq.(1) is, therefore, given by:

$$\boldsymbol{\tau}_{RB} = \boldsymbol{\tau}_H + \boldsymbol{\tau}_E + \boldsymbol{\tau}_C \tag{2}$$

where $\boldsymbol{\tau}_H$ describes the hydrodynamic forces and moments including gravity and buoyancy, $\boldsymbol{\tau}_E$ describes the environmental disturbances and $\boldsymbol{\tau}_C$ describes forces and moments created by propulsion systems and control surfaces [5]. The hydrodynamic forces and moments $\boldsymbol{\tau}_H$ can be written as:

$$\boldsymbol{\tau}_H = -\boldsymbol{M}_A\dot{\boldsymbol{\nu}} - \boldsymbol{C}_A(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{g}(\boldsymbol{\eta}) \tag{3}$$

with the first two terms representing added mass due to the inertia of the surrounding fluid, the third term represents the hydrodynamic damping and the last term represents the restoring forces. Substitution of Eq. (2) into Eq. (1) together with Eq. (3) gives the following representation of the 6 DOF dynamic equation of motion as:

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_E + \boldsymbol{\tau}_C \tag{4}$$

where

$$\boldsymbol{M} \triangleq \boldsymbol{M}_{RB} + \boldsymbol{M}_A$$

$$\boldsymbol{C} \triangleq \boldsymbol{C}_{RB} + \boldsymbol{C}_A$$

where $\boldsymbol{M}_A$ is an added inertia matrix and $\boldsymbol{C}_A$ is a matrix of hydrodynamic Coriolis and centripetal terms due to added mass. The added mass terms are derived in Fossen [5] using the concept of fluid kinetic energy. As was the case for the rigid-body dynamics, the added mass forces and moments are separated into inertia and Coriolis-centripetal matrices $\boldsymbol{M}_A$ and $\boldsymbol{C}_A$. The 6 DOF AUV model shown in Eq. (4) is highly nonlinear.

The dynamic model of the REMUS has been used in this paper as the REMUS model and control results have been widely published. The REMUS dynamic model derived by Prestero [13] has been directly implemented in the MATLAB/SIMULINK environment by Valentinis and Smart [14]. For further details of the model, reference [13] should be consulted. Two horizontal fins (stern planes) and two vertical fins (or rudders) are used to control the attitude of the REMUS vehicle. The pairs of fins move together. For the REMUS vehicle control fins, an empirical formula has been used to derive the fin lift forces and moments [13]. It should be noted that a thruster model is not used in [13], rather a constant force and moment vector is applied to the vehicle. In this paper, a detail thruster model was also implemented in the MATLAB/SIMULINK environment by Smart [14].

III. Sliding Mode Autopilot Design

Speed, steering and diving autopilots have been designed based on sliding mode control techniques for the REMUS AUV. The decoupled control design procedure can be found in [5]. Healey and Marco [8], Healey and Lienard [7], Jalving [6] and others suggest that the 6 DOF linear equations of motion can be divided into three non-interacting (or lightly interacting) subsystems, grouping certain key motion equations together for the separate function of speed, steering and diving control. Each system consists of the state variables:

- Speed system state: $u(t)$.
- Steering system states: $v(t)$, $r(t)$ and $\psi(t)$.
- Diving system states: $w(t)$, $q(t)$, $\theta(t)$ and $z(t)$.

The rolling mode, that is $p(t)$ and $\phi(t)$ is left passive in this approach. This decomposition is motivated by the slender form of the AUV.

The REMUS configuration suggests that the three subsystems can be controlled by means of a propeller with revolution $n(t)$, a rudder with deflection $\delta_R(t)$ and a stern plane with deflection $\delta_S(t)$.

The speed control autopilot design follows the design procedure described by Fossen [5] and Healey [7].

The speed control autopilot follows the following feedback control law:

$$|n|n = \frac{1}{X_{|n|n}}[(m - X_{\dot{u}})\dot{u_d} + \frac{1}{2}\rho C_D A|u|u - (m - X_{\dot{u}})\eta\tanh(\sigma/\phi)] \tag{5}$$

where $(m - X_{\dot{u}})$ is the mass of the vehicle including hydrodynamic added mass, ρ is the water density, C_D is the drag coefficient, A is the projected area, $X_{|n|n}$ is the propeller force coefficient. Thus, n is computed as the signed square root of the right-hand side of Eq. (5). The boundary layer thickness ϕ and η are chosen to be 0.1 and 4 respectively in Eq. (5).

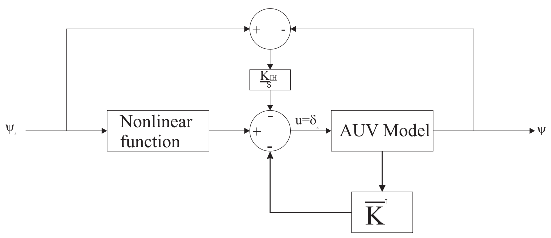

Fig. 1. Block diagram of the sliding mode steering controller with added integrator

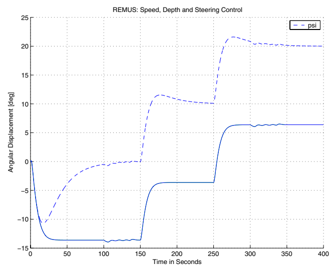

Fig. 2. REMUS angular dispalcement ψ versus time corresponding to step changes in the heading command ψ_d

The desired sway velocity during steering is specified as $v_d = 0$ while the desired yaw rate and heading angle are denoted by r_d and ψ_d.

The sliding mode steering control law δ_R is caulculated as:

$$\delta_R = -8.4753v - 1.4006r + \frac{1}{-0.3850}(-\eta)\tanh(\sigma/\phi) \quad (6)$$

The boundary layer thickness ϕ and η are chosen to be 0.1 and 1 respectively in the above equation.

The depth control law is calculated as:

$$\delta_S = 0.3402q - 0.243\theta + \frac{1}{1.1144}[-\eta\tanh(\sigma/\phi)] \quad (7)$$

The boundary layer thickness ϕ and η are chosen to be 0.1 and 1 respectively in the above equation.

To ensure the designed speed, depth and steering sliding mode autopilots achieve the desired response on the linearised model, the controllers must be tested on the nonlinear REMUS AUV model.

IV. Sliding Mode Steering Autopilot with Additional Integral Controller

When applying the sliding mode autopilot for speed, depth and steering control to the nonlinear REMUS AUV model, it was observed that the heading angle ψ exhibits a large steady-state error. The reason for this is that the sliding mode steering controller is a nonlinear controller and there is no integrator action like the conventional PID controller to eliminate the steady-state error. To overcome the problem, an integral controller which utilises the difference of the desired heading angle ψ_d and heading angle ψ as the input is introduced to the control law. The block diagram of the new sliding mode steering autopilot controller structure is shown in Figure 2 where K_{IH} is the gain of the integrator:

Figure 2 shows the response of angular dispalcement ψ corresponding to step changes in the heading command ψ_d. The heading command ψ_d is 0 for the first 150 seconds, then 10° for the next 100 seconds, then 20° for the last 150 seconds. The solid curve is the heading angle ψ without the integral controller and the dashed curve with the integrator controller ($K_{IH} = 0.0039$). It can be seen that the proposed additional integral controller eliminated the steady-state error on a heading angle ψ. For the composite sliding mode control simulation results in the following section, the integral part is included in the steering control autopilot.

V. Composite Sliding Mode Control Results by Simulation

Simulations have been performed on the full nonlinear model with the designed speed, depth and steering autopilots for the different speed command u_d. The values of u_d range from 0.7 m/s to 1.54 m/s. The simulation results show that the designed sliding mode speed, depth and steering autopilot works well under different operating forward speed conditions.

Figure 3 shows the vehicle responses corresponding to step change in the speed command u_d from 0 to 1.1 m/s applied at $t = 0$ second, the heading command ψ_d is 0 for the first 150 seconds, then 10° for the next 100 seconds, then 20° for the last 150 seconds, the depth command z_d is 10 m from $t = 0$ to $t = 100$ seconds, then $z_d = 20$ m for 200 seconds followed by $z_d = 30$ m for 100 seconds. It can be seen from this Figure that the designed autopilots control the forward speed u, the depth z and the heading angle ψ successfully.

To test the performance of the designed controllers against disturbances, wave disturbances with wave intensity $\sigma_w = 1$ have been added on $\dot{u}$, $\dot{v}$, and $\dot{w}$, respectively. Simulation results show that the speed, depth and steering controllers still work well despite wave disturbances. The results are shown in Figure 4.

To test the robustness of the designed sliding mode controllers, the nonlinear force coefficients, the nonlinear moment coefficients and the control fin coefficients of the REMUS model have been varied. These values have been increased from 5% up to 500% in the nonlinear force coefficients, the nonlinear moment coefficients and the control fin coefficients of the REMUS model. Simulation results show that the autopilot is very robust against parameter variations. Due to the page limit the results are not shown in this paper.

VI. Conclusions

A design of autopilot for a AUV based on sliding mode control methods has been reported in this paper. The dynamics of AUVs are inherently nonlinear and coupled. The sliding

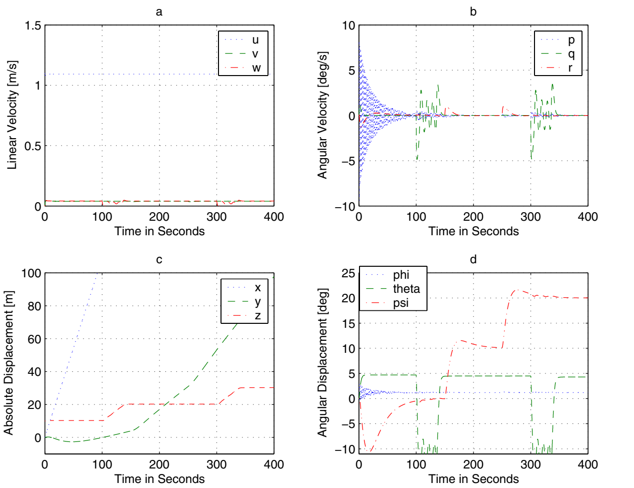

Fig. 3. REMUS linear velocities (a) u, v, w, (b) angular velocities p, q, r, (c) absolute displacement x, y, z and (d) angular displacement ϕ, θ, ψ versus time corresponding to step changes in the speed, depth and heading commands with the designed sliding mode autopilots

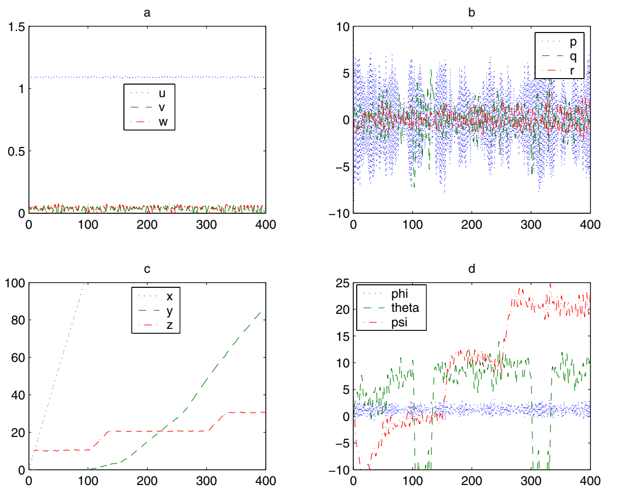

Fig. 4. REMUS linear velocities (a) u, v, w, (b) angular velocities p, q, r, (c) absolute displacement x, y, z and (d) angular displacement ϕ, θ, ψ versus time corresponding to step changes in the speed, depth and heading commands with the designed sliding mode autopilots under disturbance conditions (wave disturbances with wave intensity $\sigma_w = 1$ on $\dot{u}$, $\dot{v}$, and $\dot{w}$)

mode method can reduce the inherent coupling between the vehicle response modes that exist in AUV vehicles. A method to eliminate the steady-state error associated with sliding mode controllers has been proposed in this paper. In addition, performances have been evaluated for the sliding mode autopilot by simulation on the nonlinear model of the AUV over a variety of operating conditions. The robustness of the system was evaluated in the presence of disturbances and parameter uncertainties. The simulation results show that the nonlinear sliding mode control approach controls the speed, steering and depth of the AUV successfully.

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