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A re-configuring sliding-mode controller with adjustable robustness

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Abstract

In this paper, a controller design method for underwater vehicles is presented, which is based on re-configuration of a sliding-mode controller in case of disturbances caused by shallow water conditions. The disturbance distribution information can be obtained and used to update the corrective gain vector of the sliding-mode controller. This increases the robustness of the controller and, hence, keeps the system performance within acceptable limits. Proposed method is validated with simulations on a submarine model.

Keywords: Control re-configuration; Autonomous systems; Sliding-mode control; Disturbance rejection; Underwater vehicle autopilots

1. Introduction

Autonomous control re-configuration (Rauch, 1995) is a very important issue. Nowadays, the engineering systems are becoming more and more complex. These complex systems require robustness in order to guarantee continuous operation in case of disturbances caused by the environmental changes. In this paper, we propose a new control mechanism with active re-configuration which uses sliding-mode control technique as the baseline controller (Patton, 1997). The uncertainties caused by unanticipated disturbances are extracted by means of linear observers. The controller is re-configured with respect to uncertainty information and the

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stability of the controller is guaranteed by robustness property of sliding-mode control method. The robustness property of sliding-mode control can compensate minor disturbances. The proposed control scheme can also cope with larger disturbances by updating itself with respect to online-monitored disturbance information. Hence, the proposed scheme combines active and passive re-configuration methods.

The passive approaches of control re-configuration require a robust controller which is designed off-line in order to achieve robustness against disturbances and possible faults. Once the robust controller is designed to accommodate possible disturbances which might change the system parameters then it is not possible to re-configure the controller in case of unpredicted disturbances. The use of robust control technique as a passive re-configuring controller alone for fault accommodation can be quite risky. If disturbance and modeling uncertainties are not accounted for during the (off-line) design of the robust controller, then they might insert adverse effects on the system. Also nearly all passive control re-configuration designs in Keating et al. (1995) and and Murad et al. (1996) do not challenge the robustness problem and do not consider the smaller or incipient effects of disturbances which may happen in real applications, but only consider large effects.

There are also a great variety of active control re-configuration techniques. Control law re-scheduling (Moerder et al., 1989) is implemented mainly for flight control systems. This method requires the knowledge of the fault or disturbance characteristics and their effects on system dynamics. In return, different sets of control gains can be a priori calculated with respect to possible situations. An effective disturbance monitoring mechanism is required in order to extract disturbances accurately. By doing so, the correct control schedule can be implemented without operator supervision. The main drawback of this method is the requirement of precise fault or disturbance information otherwise it is not possible to compensate an incorrect re-scheduling.

Another active re-configuration method is pseudo-inverse method (Ostroff, 1985; Rattan, 1985). The constant feedback gain is updated in a way to approximate the nominal system in case of anticipated faults or disturbances. Gain sets are designed for all possible faults and disturbances. No fault detection or disturbance monitoring mechanism is required, but the stability of the system in case of an unanticipated fault or disturbance cannot be guaranteed.

Model following as an active re-configurable control technique is implemented for many applications with many different adaptive methods in Morse and Ossman (1990), Groszkiewicz and Bodson (1995) and Bodson (1997). For example, adaptive re-configuration via model following method uses the estimated system parameters for updating the controller scheme in case of disturbances. The problem with this method is the difficulty in estimating system parameters accurately. In some cases, the input signals for the estimators are not persistently exciting enough. In return, the updated controller parameters cannot provide the desired response.

The proposed approach is an active (on-line) control re-configuration scheme which uses the well known robust sliding-mode control method as the baseline controller of the nominal plant. Sliding-mode controller gain vector is re-configured when a fault or an uncertainty is monitored by an observer. A disturbance or fault distribution information is extracted from plant dynamics by using linear observers. This disturbance distribution information is used to adjust the robustness of the sliding-mode controller to annul the unwanted effects of disturbances on tracking performance. No pre-calculations are involved, nor are a priori information on fault or disturbance required. In case of unanticipated changes in system dynamics which can be processed as additive disturbances, the robustness of the sliding-mode controller is increased using disturbance distribution information. Chattering, the main drawback of the sliding-mode controller, is eliminated by using a soft nonlinear switching function for the nominal plant. The chattering is almost unavoidable for a plant subject to disturbances, as the control action increases extensively to compensate unwanted effects. But the stability of the on-line re-configured controller is guaranteed due to the nature of baseline sliding-mode controller in case of excessive disturbances as well as disturbance-free case. A Lyapunov function is defined in terms of a sliding manifold and along which the stability is guaranteed for sliding-mode controllers (Khalil, 2002).

Sliding-mode control scheme has been recently used for re-configuration purposes by McGookin (2003)and Yen and Ho (2000). McGookin (2003) describes the use of sliding-mode controller as a passive baseline controller to compensate the sensor fault effects. However, Yen and Ho (2000) implemented sliding-mode controller scheme for an SISO system in a way that the faults or uncertainties are detected by means of a neural network observer. The robustness of the sliding-mode controller is increased without taking care of the direction of the uncertainty. In the meantime neural network model is trained for the faulty system which causes a great deal of computational burden. In our solution a generalized MIMO system is used and the disturbance distribution vector directions are also extracted from the uncertainty information. The robustness of the sliding-mode controller is updated only using the disturbance distribution vector direction without increasing the computational burden involved appreciably.

The rest of this paper first discusses the implementation of the proposed novel approach on a submarine model (Section 2). Models of the submarine, sea and actuators are also described in Section 2. Section 3 describes the proposed novel controller together with the linear observer used to monitor and extract uncertainty information. Further, simulations are explained in Section 4. Section 4 also describes and presents how we evaluated the performance of the resulting system. Finally, the last section presents conclusions and describes possible future work.

2. Problem statement

2.1. Shallow-submerged submarine operation

In this study, the depth control of a submarine at shallow submergence under sea wave disturbances is investigated in order to imply the effectiveness of our novel approach. Shallow water operation has vital importance for conventional submarines to use their periscope and charge batteries while cruising in diesel-engine mode. However, the depth control becomes more difficult when the vessel is close to the surface due to adverse effects of sea conditions. The vessel at shallow-submerged position is effected by sea waves rather than currents in the sea that is neglected in this study.

The vehicle in this study (Dumlu and Istefanopulos, 1995) has two control surfaces, namely, the bow and stern planes. Also, the content of the trim tanks is used as a constant control input. But the content of the trim tanks is assumed to be defined and implemented prior to control activity. The depth and pitch angle measurements are performed by a hydrostatic pressure sensor and a gyroscopic system, respectively. The vehicle is assumed to be at shallow submergence and has initially constant low speed forward motion. The vehicle is also assumed to be stable in roll axis and no control activity required for roll motion. Therefore, the yaw motion which is controlled by the rudder is uncoupled from the pitch motion.

The submarine beneath the sea waves is subject to sea forces and moments. These forces are composed of first and second order parts of sinusoidal wave patterns. The first order forces tend to cancel each other along the hull of the vehicle and can be neglected for the controller design. Second order part of the wave effect tends to pull the vehicle towards to surface. The latter one becomes smaller as the depth increases. This is called *suction force*.

Equations of motion of a submarine consist of nonlinear differential equations. These equations are derived in six degrees of freedom (Fossen, 1994). Since the control action is not performed for yaw and roll axes, the pitch and heave equations are used for the controller design. For working with a linear model is much simpler than a nonlinear one, the nonlinear equations of the submarine for the pitch and heave axes have been linearized around an equilibrium point.

The adverse effects of the sea waves are modeled to include in the overall submarine model for a more realistic controller design. Sea states can be defined with respect to sea wave heights from sea state 0 (calm–glassy-) up to 9 (phenomenal) as it is shown in tabular format in Fossen (1994). In this study, the sea states from 1 (calm–rippled-) and 6 (very rough) are modeled in order to investigate the control performance for different sea wave heights.

The proposed control re-configuration scheme is implemented for the depth control of the submarine. It is aimed to keep the vehicle at submergence in order to avoid detection by FOE in case of approaching to surface as a result of suction force.

2.2. Submarine dynamics

The derivation of submarine model is investigated in detail by Dumlu and Istefanopulos (1995). Equation of motion along the z-axis (normal force) is given

$$\dot{w}(t) = \frac{Z'_w U}{Lm'_3} w(t) + \frac{1}{m'_3}(z'_{\dot{\theta}} + m')U\dot{\theta}(t) + \frac{Z'_{\ddot{\theta}} L}{m'_3}\ddot{\theta}(t) + \frac{Z'_{\delta B} U^2}{Lm'_3}\delta B(t) + \frac{Z'_{\delta S} U^2}{Lm'_3}\delta S(t) + \frac{2}{\rho L^3 m'_3}(Z_{\text{wave}}(t) + W_e(t)\cos\theta) \quad (1)$$

where w(t) is the velocity of the submarine along the z-axis, Q is the rotational velocity, θ is the pitch angle and h is the depth value, ρ is the mass density of sea water, L is the length and m is the weight of the submarine, U is the forward speed of the submarine which is 8.43 ft/s, δB is the bow plane command and δS is the stern plane command. Sea wave disturbances are Z_{wave} and M_{wave}, which are the component of sea force along the z-axis of the submarine and the moment of sea waves about the y-axis of the submarine, respectively.

Equation of motion along the y-axis (pitching moment) is given

$$\begin{aligned}\ddot{\theta}(t) = {} & \frac{M'_{\dot{w}}}{LI'_2}\dot{w}(t) + \frac{M'_w U}{L^2 I'_2}w(t) + \frac{M'_{\dot{\theta}} U}{LI'_2}\dot{\theta}(t) + \frac{M'_{\delta B} U^2}{LI'_2}\delta B(t) + \frac{M'_{\delta S} U^2}{L^2 I'_2}\delta S(t) \\ & + \frac{2mg}{\rho L^5 I'_2}(z_G - z_B)\theta + \frac{m_{\text{wave}}}{(\rho/2)L^5 I'_2}\end{aligned} \tag{2}$$

where $Q(t) = \dot{\theta}(t)$.

By substituting the hydrodynamic coefficients and other values which are given in Dumlu and Istefanopulos (1995), and substituting Eqs. (1) and (2) to each other

$$\begin{aligned}\dot{w}(t) = {} & -2.45313 \times 10^{-2} w(t) + 1.5174 Q(t) + 4.6192185 \times 10^{-2}\delta B(t) \\ & - 7.9592688 \times 10^{-2}\delta S(t) + 1.62 \times 10^{-2}\theta(t) - 2.2 \times 10^{-9} M_{\text{wave}}(t) \\ & + 3.06 \times 10^{-6} Z_{\text{wave}}(t) + 9.8 \times 10^{-5} M_{e_{\text{aux}}}, \\ \dot{Q}(t) = {} & 3.3720 \times 10^{-4} w(t) - 7.71345 \times 10^{-2} Q(t) + 4.79688 \times 10^{-4}\delta B(t) \\ & - 2.184535 \times 10^{-3}\delta S(t) - 0.003975\theta(t) + 5.42 \times 10^{-10} M_{\text{wave}}(t) \\ & - 2.20 \times 10^{-9} Z_{\text{wave}}(t) - 7.14 \times 10^{-8} M_{e_{\text{aux}}}\end{aligned} \tag{3}$$

where $M_{e_{\text{aux}}}$ is the auxiliary tank content.

These equations are the states of the submarine dynamics, pitch velocity and heave velocity. From (3), the state-space model of the submarine dynamics can be written as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{R}\mathbf{d}(t) \tag{4}$$

with

$$\begin{aligned}\mathbf{x}(t) &= [w(t), Q(t), \theta(t)]^{\mathrm{T}}, \\ \mathbf{u}(t) &= [\delta B(t), \delta S(t), M_{e_{\text{aux}}}]^{\mathrm{T}}, \\ \mathbf{d}(t) &= [Z_{\text{wave}}(t), M_{\text{wave}}(t)]^{\mathrm{T}}\end{aligned}$$

where $\mathbf{x}(t) \in \Re^n$ is the state vector, $\mathbf{u}(t) \in \Re^r$ is the control input vector and $\mathbf{y}(t) \in \Re^m$ is the measurement vector, and the values of $\mathbf{A}$, $\mathbf{B}$ are obvious from (3). The vector $\mathbf{d}(t) \in \Re^h$ is the disturbance vector representing sea force component along the z-axis and moment of sea waves about the y-axis. The matrix $\mathbf{R}$ is the disturbance distribution matrix.

2.3. Sea model

The submarine beneath the sea waves is subject to sea forces and moments. These forces are composed of first and second order parts of sinusoidal wave patterns (Richards and Stoten, 1982). The first order forces tend to cancel each other along the hull of the vehicle and can be neglected for the controller design. Second order part of the wave effect tends to pull the vehicle towards to surface. The latter one becomes smaller as the depth increases. The adverse effects of the sea waves are modeled to include in the overall submarine model for a more realistic controller design. The sea model given in this paper is the one accepted in International Towing Tank Conference (ITTC). This model describes the spectrum of the sea-level motion as (Sükan, 1985),

$$S(\omega) = \frac{8.1 \times 10^{-3} g^2}{\omega^5} \exp\left[\frac{-3.11}{H_s^2 \omega^4}\right] \tag{5}$$

where H_s is the significant wave height in meters, ω is the frequency in rad/s and $g = 9.81\ \mathrm{m/s^2}$.

Sea waves have two types of effects on ship dynamics as disturbance, one is the disturbance on force dynamics and the other one is the disturbance on moment dynamics (Borgman, 1969), which can be modeled as

$$Z_{\mathrm{wave}}(t) = \left[2.2772 \times 10^5 - 1.4552 \times 10^4 \sum_{i=1}^{N} F_i \sin\omega_{ei} t\right] \cdot \sum_{i=1}^{N} F_{1i} \sin\omega_{ei} t,$$

$$M_{\mathrm{wave}}(t) = 1.7780 \times 10^7 \cdot \sum_{i=1}^{N} F_i \cos\omega_{ei} t$$

Such a computation of $Z_{\mathrm{wave}}(t)$ and $M_{\mathrm{wave}}(t)$ is based on sampling $S(\omega)$ at N different frequencies, $\omega_{ei} (i = 1, \ldots, N)$ and obtaining F_i's (the force due the static head at the vehicle depth) corresponding to these frequencies (Dumlu and Istefanopulos, 1995; Mandzuka, 1998).

2.4. Actuator dynamics

The submarine model in (4) includes three control inputs applied to the system by three actuators. Two of the actuators that are electro-hydraulic systems are used to drive bow and stern hydroplanes. The actuator for the third input is a pump to fill or empty the auxiliary tank. As the actuators are mechanical devices their control action is limited. Limit values for bow and stern hydroplanes are $\pm 30^\circ$. A digital filter can represent the dynamics of the bow and stern hydroplanes as

$$x_h(k+1) = 0.885 x_h(k) + 0.115 u_h(k)$$

where x_h is the commanded hydroplane deflection and u_h is the actual hydroplane deflection.

3. Re-configuring sliding-mode controller design

The controller is a modified version of sliding-mode controller (Slotine and Li, 1991). Submarine dynamics is reduced to two-input-two-state form by treating pitch angle $\theta(t)$ as a known disturbance and computing the auxiliary tank content $M_{e_{\mathrm{aux}}}$ a priori separate from hydroplane inputs. Reduced state-space model of the submarine dynamics turns out to be

$$\dot{\mathbf{x}}_n(t) = \mathbf{A}_n\mathbf{x}_n(t) + \mathbf{B}_n\mathbf{u}(t) + \mathbf{R}_n\mathbf{d}(t) + \mathbf{F}\theta(t) \tag{6}$$

where

$$\mathbf{x}_n(t) = [w(t), Q(t)]^{\mathrm{T}},$$
$$\mathbf{u}(t) = [\delta B(t), \delta S(t), M_{e_{\mathrm{aux}}}]^{\mathrm{T}}$$

and, it follows from (3) and (6),

$$\mathbf{A}_n = \begin{bmatrix} -0.0245313 & 1.5174 \\ 0.0003372 & -0.0771345 \end{bmatrix}$$
$$\mathbf{B}_n = \begin{bmatrix} 0.046192185 & -0.079592688 \\ 0.000479688 & -0.002184535 \end{bmatrix},$$
$$\mathbf{F} = \begin{bmatrix} 0.0162 & 0 \\ 0 & -0.003975 \end{bmatrix}$$

For the system in (6), the state estimates $\hat{\mathbf{x}}_n(t)$ can be generated by means of a Luenberger observer, as

$$\dot{\hat{\mathbf{x}}}_n(t) = (\mathbf{A}_n - \mathbf{L})\hat{\mathbf{x}}_n(t) + \mathbf{B}_n\mathbf{u}(t) + \mathbf{F}\theta(t) + \mathbf{L}\mathbf{x}_n(t) \tag{7}$$

Defining the state estimation error as

$$\mathbf{e}(t) = \mathbf{x}_n(t) - \hat{\mathbf{x}}_n(t) \tag{8}$$

Its dynamics can be written from (6) and (8)

$$\begin{aligned}\dot{\mathbf{e}}(t) &= \dot{\mathbf{x}}_n(t) - \dot{\hat{\mathbf{x}}}_n(t), \\ &= [(\mathbf{A}_n - \mathbf{L})\mathbf{e}(t) + \mathbf{R}_n\mathbf{d}(t)]\end{aligned} \tag{9}$$

From (9), disturbance information can be extracted as

$$\mathbf{R}_n\mathbf{d}(t) = \dot{\mathbf{e}}(t) - (\mathbf{A}_n - \mathbf{L})\mathbf{e}(t) \tag{10}$$

It is known that a sliding-mode controller can be made robust to uncertainties in system dynamics when the upper bound of the uncertainty is given (Khalil, 2002). For the proposed methodology below, no information for the upper bound of the uncertainty (which may be caused by a model mismatch or disturbances) is necessary since the disturbance information obtained in (10) is used as an additive term in the equivalent control part of the control action.

In order to achieve all states of the system in (6) to track the given desired trajectories at the same time, the switching surface function (Edwards and Spurgeon, 1998) can be defined as follows:

$$\mathbf{s}(t) = \tilde{\mathbf{x}}(t) + \mathbf{\Lambda} \int \tilde{\mathbf{x}}(t)\mathrm{d}t \tag{11}$$

where $\mathbf{s}$ is the sliding surface vector, $\mathbf{\Lambda}$ is a square matrix which defines the slopes of the sliding surfaces, $\tilde{\mathbf{x}}$ is the tracking error for the state vector and defined as

$$\tilde{\mathbf{x}} = \mathbf{x}_n - \mathbf{x}_\mathrm{d}$$

A Lyapunov function can be defined as

$$\mathbf{V} = \frac{1}{2}\mathbf{s}^\mathrm{T}\mathbf{s}$$

which is positive definite and it is required that the condition $\dot{\mathbf{V}} = \dot{\mathbf{s}}s < 0 \quad (\forall t > 0)$ must be satisfied for overall system response to be stable which states the attractive condition for the sliding-mode control (Slotine and Li, 1991; Khalil, 2002). First derivative of sliding surface function follows from (6) and (11)

$$\dot{\mathbf{s}}(t) = \mathbf{A}_n\mathbf{x}_n(t) + \mathbf{B}_n\mathbf{u}(t) + \mathbf{R}_n\mathbf{d}(t) + \mathbf{F}\theta(t) - \dot{\mathbf{x}}_\mathrm{d}(t) + \mathbf{\Lambda}\tilde{\mathbf{x}}(t) \tag{12}$$

Following (Slotine and Li, 1991)

$$\mathbf{B}_n\mathbf{u}_\mathrm{eq}(t) = [-\mathbf{A}_n\mathbf{x}_n(t) - \mathbf{R}_n\mathbf{d}(t) - \mathbf{F}\theta(t) + \dot{\mathbf{x}}_\mathrm{d}(t) - \mathbf{\Lambda}\tilde{\mathbf{x}}(t)] \tag{13}$$

or

$$\mathbf{u}_\mathrm{eq}(t) = \mathbf{B}_n^{-1}[-\mathbf{A}_n\mathbf{x}_n(t) - \mathbf{R}_n\mathbf{d}(t) - \mathbf{F}\theta(t) + \dot{\mathbf{x}}_\mathrm{d}(t) - \mathbf{\Lambda}\tilde{\mathbf{x}}(t)] \tag{14}$$

where $\mathbf{u}_\mathrm{eq}$ is the equivalent control term of the overall controller which guarantees that the system states track the desired trajectories. It is clear that all terms in (14) are known except disturbance information. Here, $\mathbf{R}_n\mathbf{d}$ can be replaced by its estimate obtained from (10). To satisfy the sliding condition, a corrective control term is used for sliding-mode controllers. The overall controller with the corrective control term will be derived as (Slotine and Li, 1991; Fossen, 1994)

$$\mathbf{u}(t) = \mathbf{u}_\mathrm{eq}(t) - \mathbf{k}\mathrm{sat}\left(\frac{\mathbf{s}}{\varphi}\right) \tag{15}$$

where $\mathbf{k}$ is the corrective gain vector which is used to guarantee a sliding regime on the switching surface vector $\mathbf{s}(t)$ and sat($\mathbf{s}$) is the saturation function with respect to each variable of $\mathbf{s}$ sliding surface vector. As the disturbance information, $\mathbf{R}_n\mathbf{d}$, is inserted into the controller scheme, the controller runs in a re-configuring adaptive manner and can cope with sea wave disturbances.

4. Design example and simulation results

Each disturbance distribution vector term has been inserted into the standard sliding-mode controller as an additive gain as can be seen in (14). In other words, the controller is adopted to the system dynamics whenever there is a change in sea states. The submarine depth control for sea state 1 situation with respect to a given desired trajectory up to 30 ft (≅10 m) depth is performed with the proposed sliding-mode control scheme and the results are evaluated.

The depth velocity of the submarine is given as (Dumslu and Istefanopulos, 1995)

$$\dot{h}(t) = w(t)\cos\theta(t) - U\sin\theta(t) \tag{16}$$

For small angles, the desired depth dynamics can be written as

$$\dot{h}_{\mathrm{d}}(t) = w_{\mathrm{d}}(t) - U\theta_{\mathrm{d}}(t) \tag{17}$$

which is a combination of desired heave velocity w_{d} and desired pitch angle θ_{d}. The desired pitch angle trajectory is chosen to be 0° during the simulation, then, the desired heave velocity dynamics turns out to be

$$w_{\mathrm{d}}(t) = \dot{h}_{\mathrm{d}}(t) \tag{18}$$

So, the desired heave velocity can be obtained by differentiating the profile of desired depth h_{d}. In the simulation, the depth profile given in Fig. 1 is used, which corresponds to a depth of 30 ft (≅10 m).

It looks like that there is excessive chattering on the control planes when the control commands are observed in Fig. 2. This is not true if a shorter duration of the hydroplane activity is taken into account. It can be seen in Fig. 3 which shows the control activity detail of 5 s that the variation of control action is acceptable and implementable. Depth and pitch error values are much better than being just satisfactory (less than 0.025 ft ≅0.75 cm) as can be seen in Fig. 4.

The same scenario is simulated also with sea state 6. The control activity for a duration of 5 s is shown in Fig. 5, where it can be seen that the variation of the control action is within implementable limits. As compared to the sea state 1 scenario control inputs increase and the saturation of the bow plane inputs causes an increase and saturation for the stern plane inputs. However, the response shown in Fig. 6 is still within acceptable limits. Depth error is around 1 ft (≅30 cm) and pitch error is around 0.2°. That means, the proposed scheme re-configures the controller structure in order to compensate adverse sea affects. On the other hand, a sliding-mode controller based on the nominal plant where the disturbances are not taken into account, performs unsatisfactorily which can be seen in Fig. 7. By comparing Figs. 1 and 7, it can be said that the submarine cannot leave the sea surface because of the suction force.

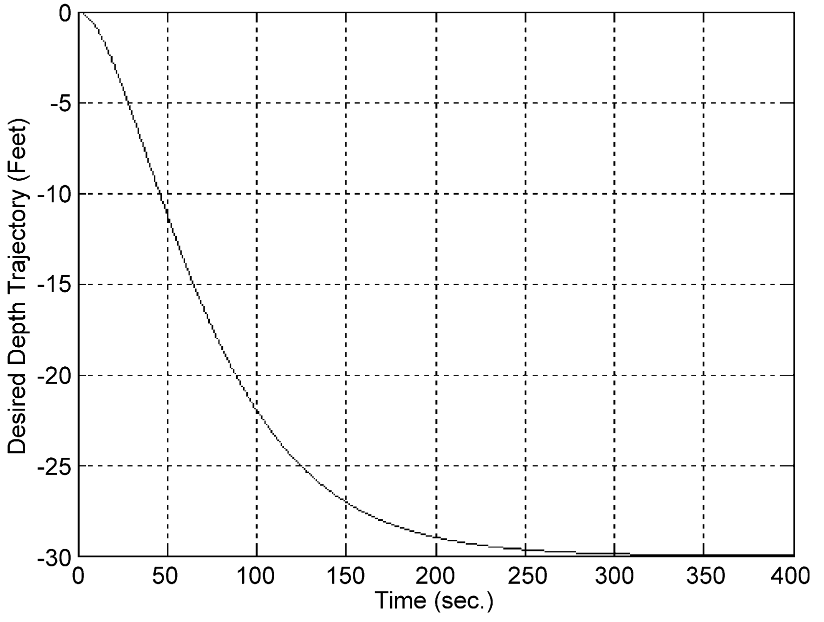

Fig. 1. Desired depth trajectory.

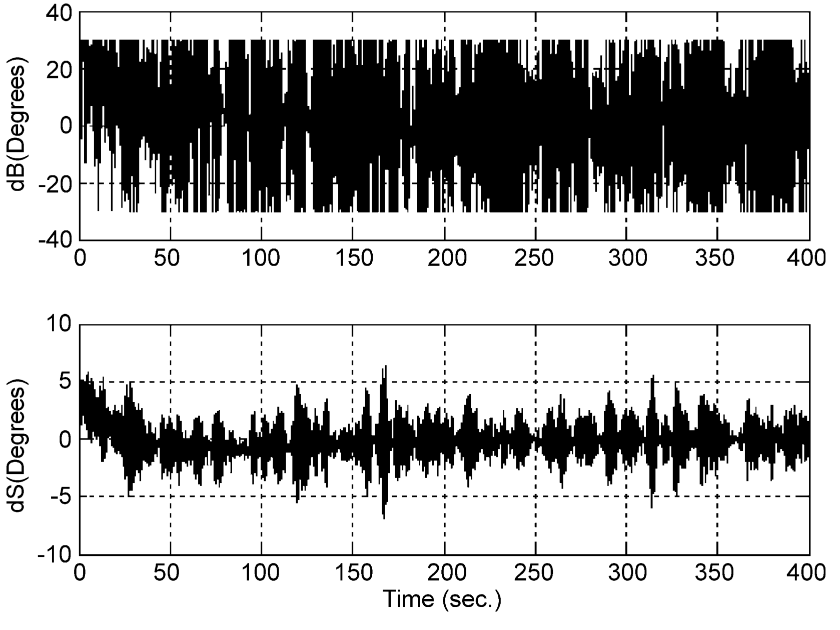

Fig. 2. Bow and stern plane commands for sea state 1 with proposed scheme.

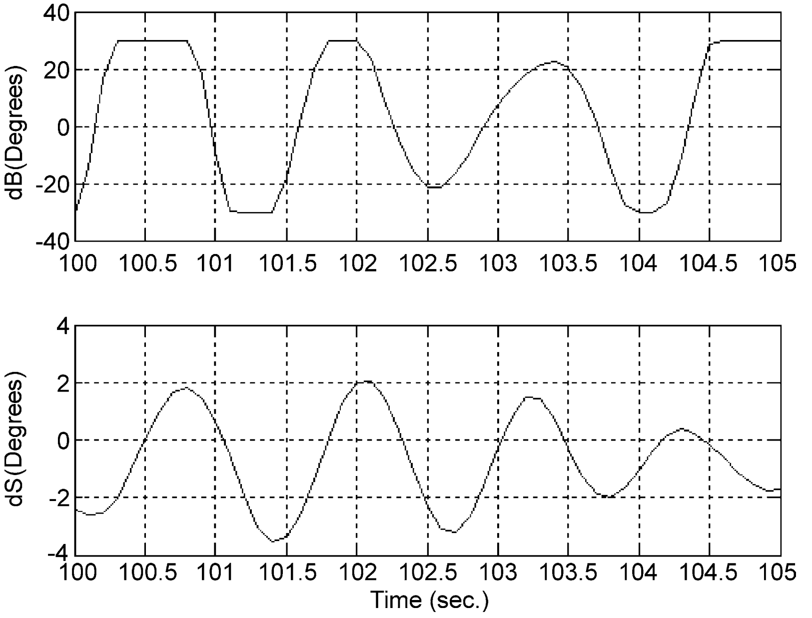

Fig. 3. Bow and stern plane commands for sea state 1 with proposed scheme in a smaller scale.

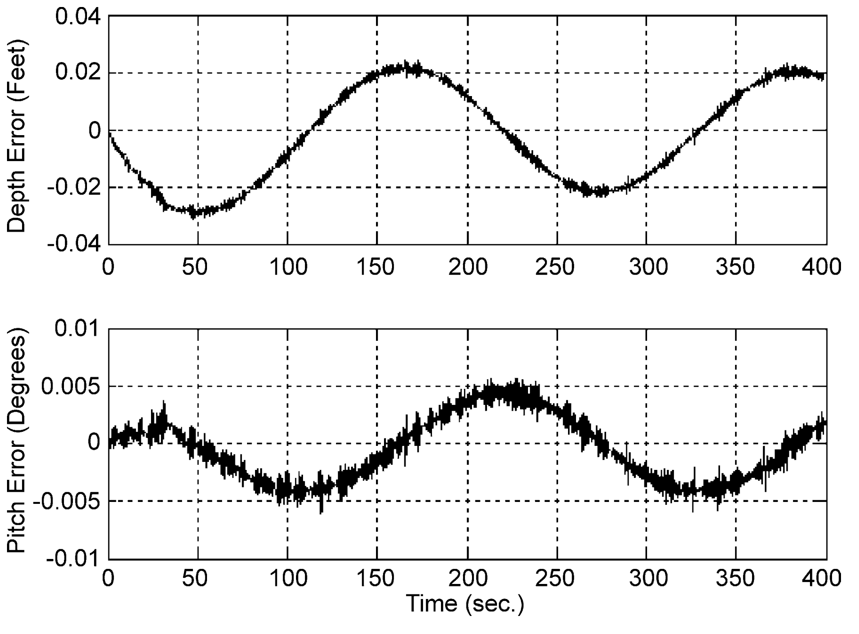

Fig. 4. Depth and pitch error values for sea state 1 with proposed scheme.

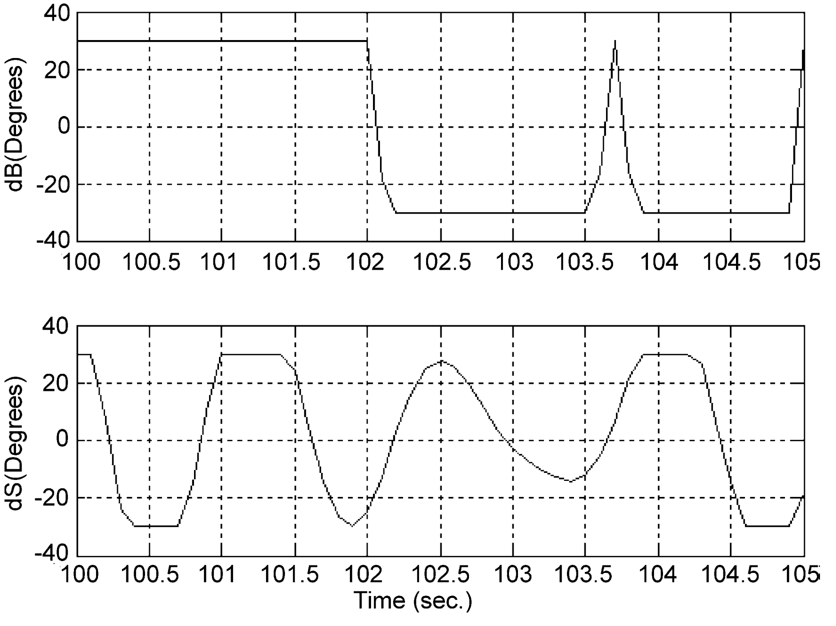

Fig. 5. Bow and stern plane commands for sea state 6 with proposed scheme in a smaller scale.

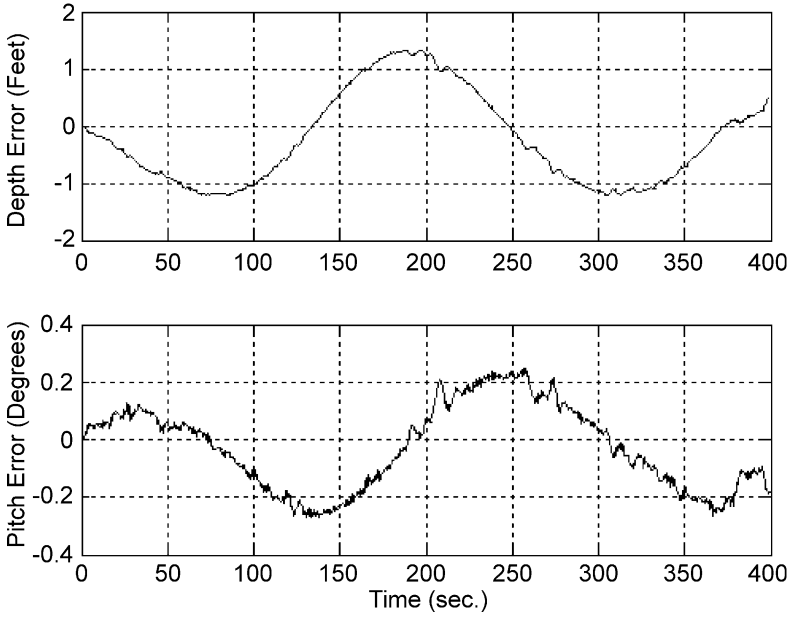

Fig. 6. Depth and pitch error values for sea state 6 with proposed scheme.

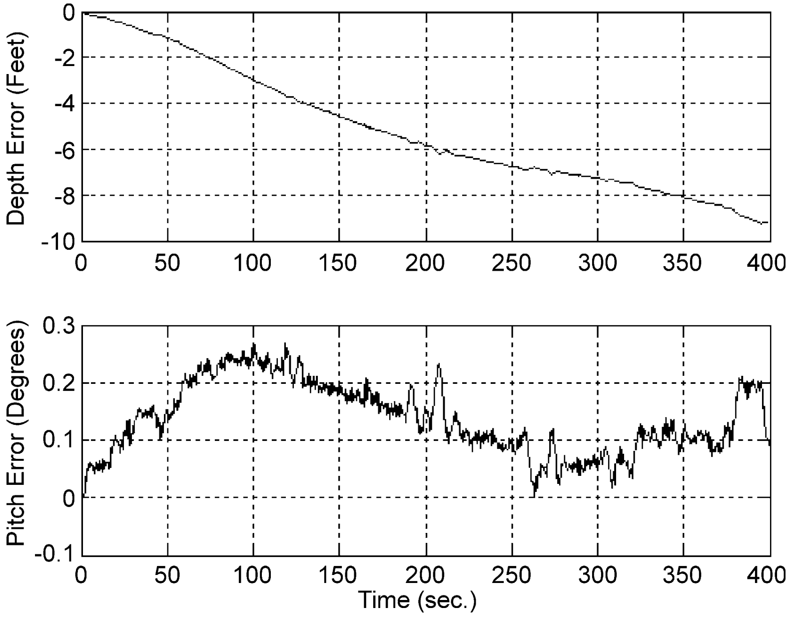

Fig. 7. Depth and pitch error values for sea state 6 with standard scheme.

5. Conclusions

A sliding-mode controller has been proposed to compensate primarily the sea wave disturbances on the submarine. The information on sea waves or other disturbances caused by model mismatch have been obtained by a state observer.

A sliding-mode controller designed by ignoring the disturbances cannot cope with excessive environmental changes but the proposed scheme gives satisfactory results under such disturbances. Sliding-mode controller designed with Lyapunov approach is modified by updating the controller using the disturbance information. Hence, the robustness of the controller is adjusted on-line and the overall performance of the controller is enhanced to overcome the disturbances caused by sea waves during shallow water operation.

Such an approach is very useful for real case applications of this field. In return, a re-configuring robust controller can be obtained in order to perform the tasks expected from a submarine. The simulations tested the applicability of the proposed scheme on a large-scale submarine. However, the same controller scheme is a good candidate for autonomous underwater vehicles (AUV) which are required to operate accurately and reliably in harsh marine environment (Lapierre et al., 2003).

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