

Design of Dynamic Positioning Control System for an ROV with Unknown Dynamics Using Modified Time Delay Estimation

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ABSTRACT

In this paper, a control system is designed for dynamic positioning of an ROV with unknown dynamics, subject to external disturbances using passive arm measurements. To estimate uncertain dynamics and external disturbances, a new method based on time delay estimation (TDE) is proposed. The proposed TDE, not only maintains the advantages of conventional TDE, but also eliminates its sensitivity to sensor noise and fast-varying external disturbances which in turn, results in smooth control signal. The proposed control system is considered as a nonlinear PD-type controller together with feedforward of estimated dynamics and disturbances. This structure presents good performance against uncertainties and external disturbances which is guaranteed via stability analysis presented. To evaluate the performance of proposed TDE, simulations are conducted and comparison are made with conventional TDE. Besides, the performance of the proposed control system is compared with conventional time delay controller (TDC) and PID controller to verify its performance. Simulations show high accuracy and superior performance of the proposed control system.

1. Introduction

ROVs and AUVs play an important part in submarine operations such as inspection, equipment installation, scientific and military operation and exploration. To operate under harsh environmental conditions and maintain position and attitude, ROVs and AUVs are equipped with Dynamic positioning (DP) control systems not only to increase accuracy but also to decrease the work load on operators and result in increased safety factor [1].

Of the biggest challenges in dynamic positioning operations can be the parametric uncertainties due to hydrodynamic effects, unknown external disturbances and accurate measurement of vehicle position be mentioned. Different control methods are considered in the literature to deal with these issues.

Application of robust controllers to deal with uncertainties and external disturbances has been considered for AUVs and ROVs in several works. Positioning of an ROV in horizontal plane was considered in [2] using sliding mode controller. Later, Healey and Lienard considered the application of multivariable sliding mode controller for controlling an AUV in steering and diving planes in [3]. In [4], a second order chattering free sliding mode controller was developed for positioning and trajectory tracking

of an ROV. Control of an ROV in the horizontal plane using H_∞ control method was considered in [5].

For plants with uncertainty, adaptive control is better compared to robust control methods in that the adaptation is performed with little or no bounds on the uncertainties [6]. However, adaptive control is applicable for adaptation of constant or slowly varying parameters. Also, linear parameterization of uncertainties is generally essential for deriving control laws. Different adaptive methods are utilized for positioning control of ROVs in horizontal plane and six degrees of freedom. In [7-8], adaptive and adaptive sliding mode controllers were designed for control of an ROV in horizontal plane. Experimental studies on ODIN ROV in six degrees of freedom are conducted in [9]. Comparison of adaptive controller with different control methods was conducted in [10]. Application of adaptive fuzzy sliding mode controller was considered in [11] and adaptive backstepping sliding mode controller was used in [12].

Application of online estimation techniques is another method to deal with uncertainties and external disturbances. Different methods are considered for online estimation of disturbances and unknown dynamics. In [13-17], extended state observers were considered to estimate unknown dynamics and external

disturbances. Neural networks and fuzzy control systems are commonly used to estimate uncertainties and external disturbances in several works [18-20].

Another method to deal with uncertainties and external disturbances is the time-delay estimation (TDE). In time delay estimation, previous system information, namely, vehicle acceleration and control signal are used to obtain estimation of unknown dynamics and external disturbances. The feedforward of estimated disturbances and unknown dynamics is considered to provide acceptable performance from control system. Application of time delay estimation was first considered for control of robotic manipulators in [21]. They combined TDE with sliding mode controller to reduce the gains of the discontinuous term.

The application of TDE for an underwater vehicle was considered in [6]. In this work, unknown dynamics were estimated by TDE and compensated for by a feedforward term introduced into a nonlinear PD-type controller. However, it was assumed that all system states are available. Experimental studies of TDE-based integral sliding mode controller on an AUV were considered in [22]. They employed Doppler Velocity Log (DVL) for obtaining AUV velocity. Moreover, Utilizing DVL in control system of the vehicle results in smaller sampling rates and increases the time delay. Besides, application of DVL is prone to integration drift and cannot be used in long-term applications such as DP, which require accurate and drift-free position signal of the vehicle.

For dynamic positioning operations, position and attitude of the ROV is required with high accuracy. To this effect, different measurement systems can be utilized in practice, among which, passive arm provides position and attitude with great accuracy, Figure 1. Passive arm can be considered as a robotic arm with passive joints. P_1 and P_2 are the connection points of the passive arm to ROV and underwater structure, respectively. Electromagnetic attachment system (EMAS) or vacuum cup may be used to attach passive arm to underwater structures. By measuring the joint angles with high accuracy, and through direct kinematics, one can obtain the position and orientation of the ROV with respect to point P_2 . This would enable the ROV to have measurement of position and orientation at high sampling rates and accuracies and is free from drift.

In this paper, a new approach is proposed based on TDE which relies on passive arm measurements for DP of an ROV. The main feature of this approach is that time history of system dynamics is considered so that smooth estimate of unknown dynamics and external disturbances is obtained based on the mean value of dynamics over a short period of time. Furthermore, stability analysis of the proposed method is investigated. A simple but practical controller is utilized based on the estimated dynamics. The proposed structure entails the following advantages: i)

significantly reduces the sensitivity of conventional TDE to sensor noise; ii) eliminates the sensitivity of conventional TDE against fast-varying disturbances; iii) provides smooth estimation of external disturbances and unknown dynamics which results in smoother control signal; iv) compared to PID-type controllers, which are designed in [23-26], it provides better positioning accuracies and control signal; v) increases the sampling rate so that smaller time delays can be achieved compared to sensors such as DVL.

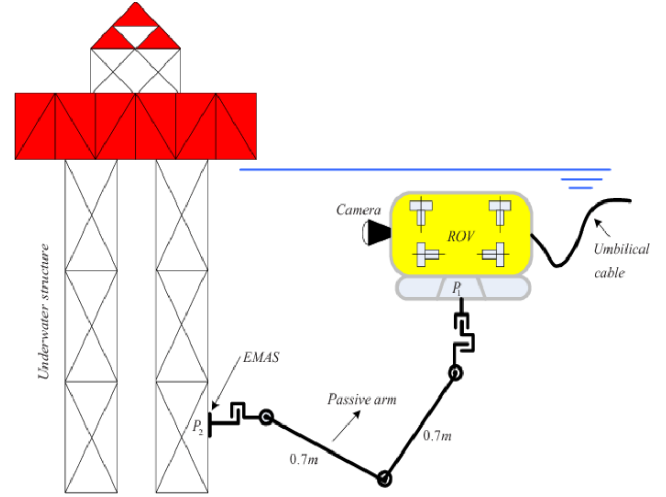


Figure 1. Dynamic positioning of an ROV with passive arm measurements [26]

2. Governing Equations of ROV

The governing equations of underwater vehicles are obtained with respect to two different coordinate systems, namely, inertial coordinate system, $\{x_i, y_i, z_i\}$, and body-fixed coordinate system, $\{x_b, y_b, z_b\}$, Figure 2, as

$$\dot{\eta} = J(\eta)v$$

$$M\dot{v} + C_{RB}(v)v + N(v_r)v_r + g(\eta) = \tau + d \quad (1)$$

where $\eta = [x, y, z, \varphi, \theta, \psi]$ is the position and attitude vector in inertial coordinate system and $v = [u, v, w, p, q, r]$ is the velocity vector in body-fixed frame. v_r is the relative velocity of vehicle with respect to water which takes into account the velocity of ocean currents, v_{cur} , as $v_r = v - v_{cur}$. $M = M_{RB} + M_A$ is the inertia matrix including the added mass, $C_{RB}(v)$ is the rigid body Coriolis and centripetal matrix, $N(v_r) = C_A(v_r) + D(v_r)$ which represents the effects of Coriolis and centripetal forces due to added mass and damping effects. $g(\eta)$ is the restoring forces due to weight and buoyancy, τ is the forces provided by controller and d represents the external disturbances including the effects of passive arm. $J(\eta)$ is the transformation matrix between inertial and body-fixed frame defined as

$$J(\eta) = \begin{bmatrix} J_1 & 0 \\ 0 & J_2 \end{bmatrix} \quad (2)$$

where

$$\begin{aligned}
 J_1 &= \begin{bmatrix} c\psi c\varphi & -s\psi c\varphi + c\psi s\varphi s\theta & s\varphi s\psi + c\varphi s\theta c\psi \\ c\theta s\psi & c\varphi c\psi + s\varphi s\theta s\psi & -s\varphi c\psi + c\varphi s\theta s\psi \\ -s\theta & s\varphi c\theta & c\varphi c\theta \end{bmatrix} \\
 J_2 &= \begin{bmatrix} 1 & s\varphi t\theta & c\varphi t\theta \\ 0 & c\varphi & -s\varphi \\ 0 & s\varphi/c\theta & c\varphi/c\theta \end{bmatrix} \quad (3)
 \end{aligned}$$

where $s(\cdot)$, $c(\cdot)$ and $t(\cdot)$ refer to $\sin(\cdot)$, $\cos(\cdot)$ and $\tan(\cdot)$, respectively.

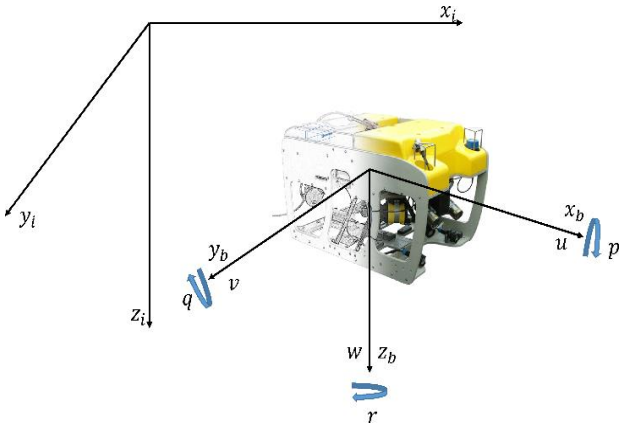


Figure 2. Inertial and body-fixed coordinate systems [1]

ROVs are designed such that roll and pitch angles are almost zero; By further simplification and assuming constant yaw angle ($\psi = \psi_c$ and $\dot{\psi} \approx 0$), the vehicle motion can be considered in three degrees of freedom. The following sets of equations can be obtained for surge, sway and heave directions.

$$\begin{aligned}
 \dot{\eta} &= R(\psi_c)v \\
 \bar{M}\dot{v} &= \tau + H \quad (4)
 \end{aligned}$$

where \bar{M} is the nominal value of inertia matrix, $R(\psi_c)$ is the transformation matrix and H is the unknown dynamics of the ROV, which are defined, respectively, as

$$R = R(\psi_c) = \begin{bmatrix} c\psi_c & -s\psi_c & 0 \\ s\psi_c & c\psi_c & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$H = \begin{bmatrix} (m_u - \bar{m}_u)\dot{u} + k_u u + k_{u|u}|u| - d_1 \\ (m_v - \bar{m}_v)\dot{v} + k_v v + k_{v|v}|v| - d_2 \\ (m_w - \bar{m}_w)\dot{w} + k_w w + k_{w|w}|w| - d_3 \end{bmatrix} \quad (6)$$

where m_u , m_v and m_w are ROV masses including the added mass, \bar{m}_u , \bar{m}_v and \bar{m}_w are the corresponding nominal values and k_u , k_v and k_w are linear damping coefficients along the x , y and z axes, respectively. $k_{u|u}$, $k_{v|v}$ and $k_{w|w}$ represent nonlinear damping terms along the respective axes and d_1 , d_2 and d_3 are the unmodeled dynamics and external disturbances.

3. Proposed Modified Time Delay Control and Estimation

The block diagram of the control system is shown in Figure 3. The control objective is to drive the ROV to the desired position in the presence of unknown dynamics and external disturbance. To estimate unknown dynamics of the ROV, i.e. H , consider the second equation of (4) as

$$H = \bar{M}\dot{v} - \tau \quad (7)$$

By introducing a small time delay into \dot{v} and τ , one may obtain the following relation for estimation of H as

$$H \approx \hat{H} = \bar{M}\dot{v}_{(t-\delta)} - \tau_{(t-\delta)} \quad (8)$$

where δ is the time delay introduced into the control law and acceleration to obtain \hat{H} .

This method, TDE, is simple in that, it only requires the introduction of time delay into system dynamics to obtain estimate of external disturbances and designing other structures such as disturbance observers or the introduction of integral term into the controller is not required. However, TDE leads to significant sensitivity of the control signal to sensor noise because of numerical differentiation for calculating acceleration of the vehicle from

$$\dot{v}_{(t-\delta)} = R^{-1} \frac{(\eta_t - 2\eta_{(t-\delta)} + \eta_{(t-2\delta)})}{\delta^2} \quad (9)$$

This effect is intensified when the sampling rate is high, since for lower δ , the sensitivity to sensor noise increases significantly. This may lead to instability of the vehicle and mechanical wear and tear of the thrusters. However, application of lower sampling rates will lead to large time delays and deteriorate the performance of control system.

To deal with this problem, so that high sampling rates are maintained and significant reduction of sensitivity to sensor noise is achieved, the following method is proposed for estimating H . In this method, instead of estimating H with a single set of data, a series of previous data are used as

$$\hat{H}_m = \frac{\sum_{p=1}^n (\bar{M}\dot{v}_{(t-p\delta)} - \tau_{(t-p\delta)})}{n} \quad (10)$$

where n is the total number of data considered in the time period $n\delta$. This modification, due to high sampling rate of passive arm and high bandwidth of the vehicle, will maintain the advantages of conventional TDE provided that δ is sufficiently small. In practice δ is considered as the sampling rate which is in the range $0.01 - 0.005s$ for passive arm [6, 24].

The proposed control law, based on modified TDE, can be defined as

$$\tau = \bar{M}R^{-1} \left(\ddot{\eta}_d - k_p(\eta - \eta_d) - k_d(\dot{\eta} - \dot{\eta}_d) \right) - \hat{H}_m \quad (11)$$

where η_d and $\dot{\eta}_d$ are the desired values of η and $\dot{\eta}$, respectively, and $\ddot{\eta}_d$ is the desired acceleration. k_p and k_d are positive diagonal gain matrices of appropriate dimensions.

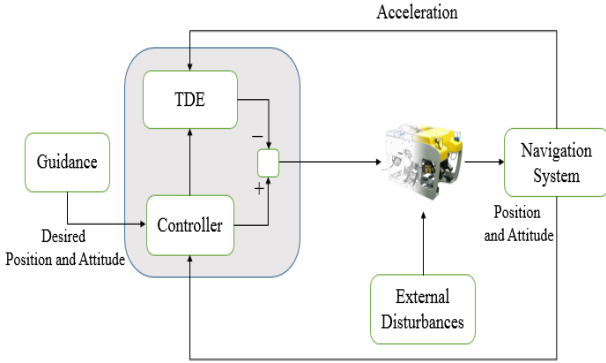


Figure 3. Block-diagram of control system

4. Stability Analysis

Consider the system (4), the controller (11) and the estimation (10). Transforming Eq. (4) into inertial coordinate system may result in

$$\begin{aligned} \bar{M}R^{-1}\ddot{\eta} \\ = \bar{M}R^{-1} \left(\ddot{\eta}_d - k_p(\eta - \eta_d) - k_d(\dot{\eta} - \dot{\eta}_d) \right) \\ + (H - \hat{H}_m) \end{aligned} \quad (12)$$

which shows that the error dynamics is obtained as

$$\ddot{e} + k_d\dot{e} + k_p e = R\bar{M}^{-1}(H - \hat{H}_m) \quad (13)$$

The term $R\bar{M}^{-1}(H - \hat{H}_m)$ can be formulated as

$$\begin{aligned} R\bar{M}^{-1}(H - \hat{H}_m) \\ = R\bar{M}^{-1} \frac{\sum_{p=1}^n nH(t) - H(t - p\delta)}{n} \end{aligned} \quad (14)$$

It can be considered that

$$H(t) - H(t - p\delta) = \varepsilon_p(t) \quad (15)$$

where $\varepsilon_p(t)$ is bounded for small δ and converges to zero as $\delta \rightarrow 0$, provided that \bar{M} is an acceptable estimate of M [6]. Consequently,

$$\varepsilon(t) = R\bar{M}^{-1} \frac{\sum_{p=1}^n \varepsilon_p(t)}{n} \quad (16)$$

which is bounded because of boundedness of each $\varepsilon_p(t)$. Therefore, the error dynamics can be formulated as

$$\ddot{e} + k_d\dot{e} + k_p e = \varepsilon(t) \quad (17)$$

which results in input to state stability, bounded-input bounded-output stability and global uniform ultimate

boundedness of closed-loop error dynamics for time-varying disturbances and global exponential stability of error dynamics for constant or very slowly-varying dynamics.

5. Simulation Studies

Simulations are carried out in two different cases to verify the performance of modified TDE and proposed control system. First, the modified TDE is compared with conventional TDE of [6] in terms of estimation accuracy and sensitivity to sensor noise. Later, the performance of the proposed control system is compared with the structure of [6] and PID controller. All the simulations are conducted in MATLAB/Simulink.

The controller parameters are taken as $k_p = \text{diag}(5, 2.3, 5.1)$, $k_d = \text{diag}(12, 7.2, 13.2)$ and $\bar{M} = \text{diag}(300, 500, 500)$. The parameters of the ROV are given in Table 1 as

Table 1. Parameters of ROV

m_u (kg)	m_v (kg)	m_w (kg)
391.5	639.6	639.6
k_u	k_v	k_w
16	131.8	65.6
$k_{u u }$	$k_{v v }$	$k_{w w }$
229.4	328.3	296.8

The disturbances are considered as follows.

- For the first 60 seconds, there is no external disturbance.
- After 60 seconds, external disturbances are considered based on Wiener process [27]. This model for each degree of freedom is defined as

$$\dot{d} = E_d w \quad (18)$$

where E_d is the amplitude of the Gaussian white noise w . For simulation, it is considered that $E_d = 300I$.

- In sway direction, to model wave-induced motions, a sinusoidal disturbance of amplitude 200 N and frequency of $\pi/5$ (rad/s) is considered from time 60 s.

The time delay is taken $\delta = 0.01$ s and the number of previous data are taken as $n = 10$.

5.1. Time Delay Estimation

First, the performance of the proposed TDE is considered in estimating disturbances and unknown dynamics and the results of the simulations are presented in Figure 4. To evaluate the sensitivity of both methods to measurement noise, position measurement noise is considered. For this, a band-limited white noise is considered with noise power of 10^{-10} .

Figures 4a-4c show that the proposed TDE has estimated unknown dynamics and external disturbance

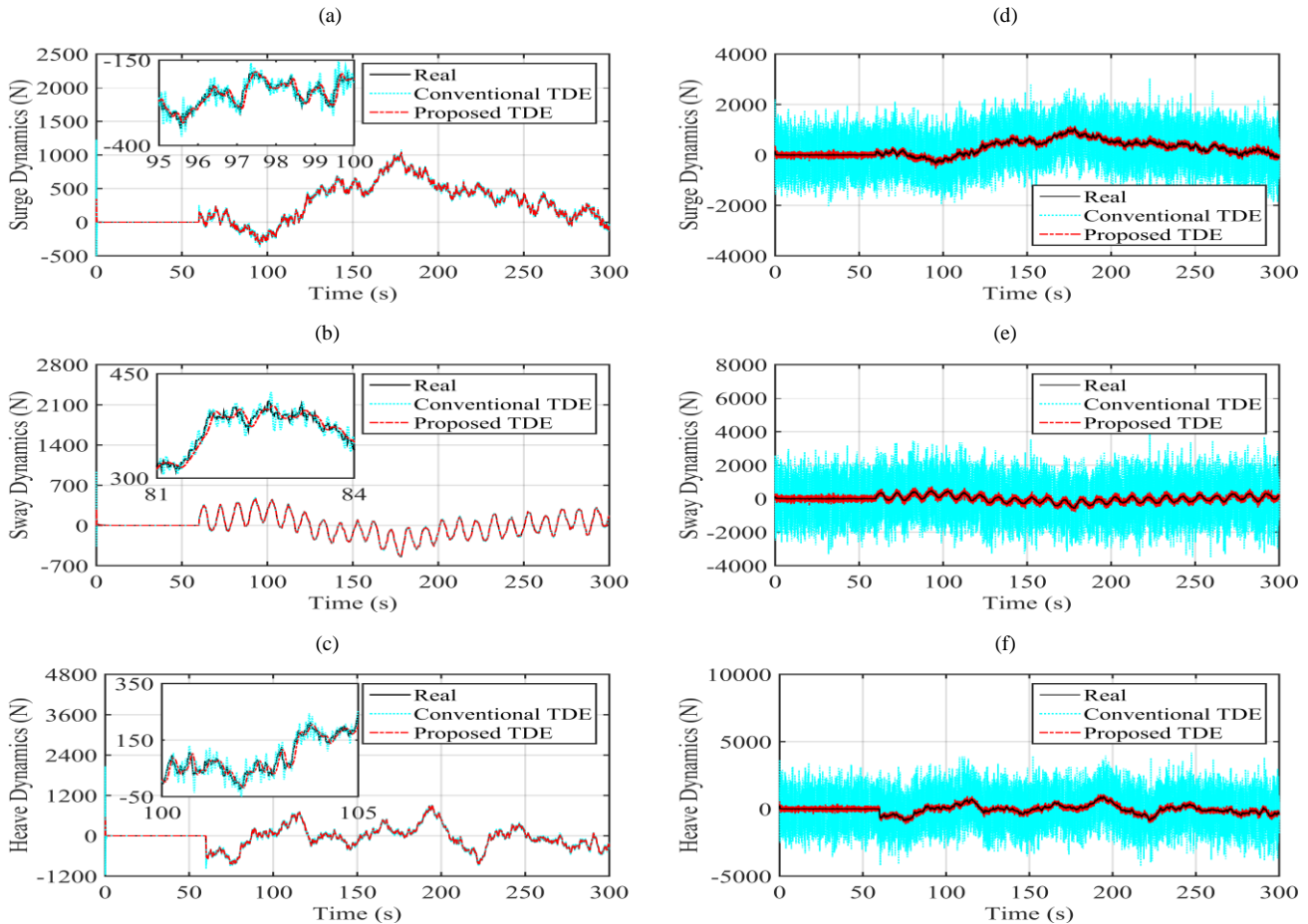


Figure 4. Simulation result for comparing conventional TDE and proposed TDE for estimation of ROV dynamic for corresponding degrees of freedom; (a)-(c): Without position sensor noise, (d)-(f): With position sensor noise effects.

with high accuracy and a smooth signal is obtained for all degrees of freedom compared to conventional TDE. The smoothness of the proposed TDE relies on the averaging method taken into consideration. In terms of sensor noise effect, Figure 4d-4f, conventional TDE has led to significant oscillations of random nature. These oscillations, when considered in closed-loop control system, lead to significant oscillations in control signal which is quite inapplicable. However, the proposed TDE has estimated unknown dynamics quite well and the effect of sensor noise is not so much evident.

5.2. Control System

The performance of control systems is presented in terms of position and control signal for different degrees of freedom in Figure 5.

The performance of controllers in terms of position signal shows that the proposed control system and the structure of [6] has maintained the position of ROV at desired values within an accuracy of a couple of millimeters in all degrees of freedoms. The control systems based on TDE has led to better results compared to PID controller. The application of PID controller, leads to significant overshoot in transients and has resulted in significant errors in steady-state part. The superior performance of TDE based controllers is outlined in sway direction where the

position of ROV is maintained with excellent accuracy, whereas, PID controller has led to oscillations of high amplitude.

The proposed control system, despite providing similar control signal to PID controller, has led to better positioning accuracies which is due to estimation of unknown dynamics and compensation by a feedforward term. It is as if the disturbances are compensated for prior to causing deviations from desired position, whereas, PID controller is based on error growth and compensates for external disturbances after the error is introduced into system. This feature makes the proposed control system more fast-responding than PID controller. This effect is evident when ROV is subjected to external disturbances at time 60 s. The proposed controller has eliminated the effects of external disturbances and resulted in better accuracies compared to PID controller, which shows that the proposed controller responds faster to external disturbances.

The application of integral term in PID controller has led to high level of control effort in transients which is 2-3 times more than the control signal of proposed control system. Besides, the control signal of structure of [6] is similar to control signal of PID controller in transients and leads to high level of control effort,

whereas the proposed structure leads to smooth estimation in transients and decreases the control effort. In terms of sensor noise effect in control signal, Figures 5d-5f, PID controller and proposed structure have provided control signals less sensitive to sensor noise, while, significant variations are evident in control signal provided by structure of [6]. It is also evident that the proposed control system has provided better control signal compared to PID controller.

6. Conclusion

In this paper, a modified time delay estimation based control system was introduced for precise positioning of an ROV with unknown dynamics and subject to external disturbances using passive arm measurements. The modification introduced into conventional time delay estimation made it less sensitive to measurement noise and provided smooth estimates of fast-varying external disturbances. The performance of the proposed TDE was also evaluated under sensor noise.

It was surprisingly witnessed that sensor noise effect was significantly reduced both in estimation and control signals. To evaluate the performance of proposed control system, simulations were conducted and the results showed that the proposed control system has maintained the accuracy of conventional method while removing its sensitivity to sensor noise and fast varying disturbances, which in turn, results in smoother control signal applicable by thruster system. Besides, the proposed control system improved the control signal in transients compared to conventional method and PID controller which the former relies on conventional TDE and the latter depends on integral action. The stability analysis was also presented for error dynamics of the closed-loop control system and it was shown that the error dynamics is GUUB for fast-varying disturbances and GES for constant or very slowly-varying disturbances.

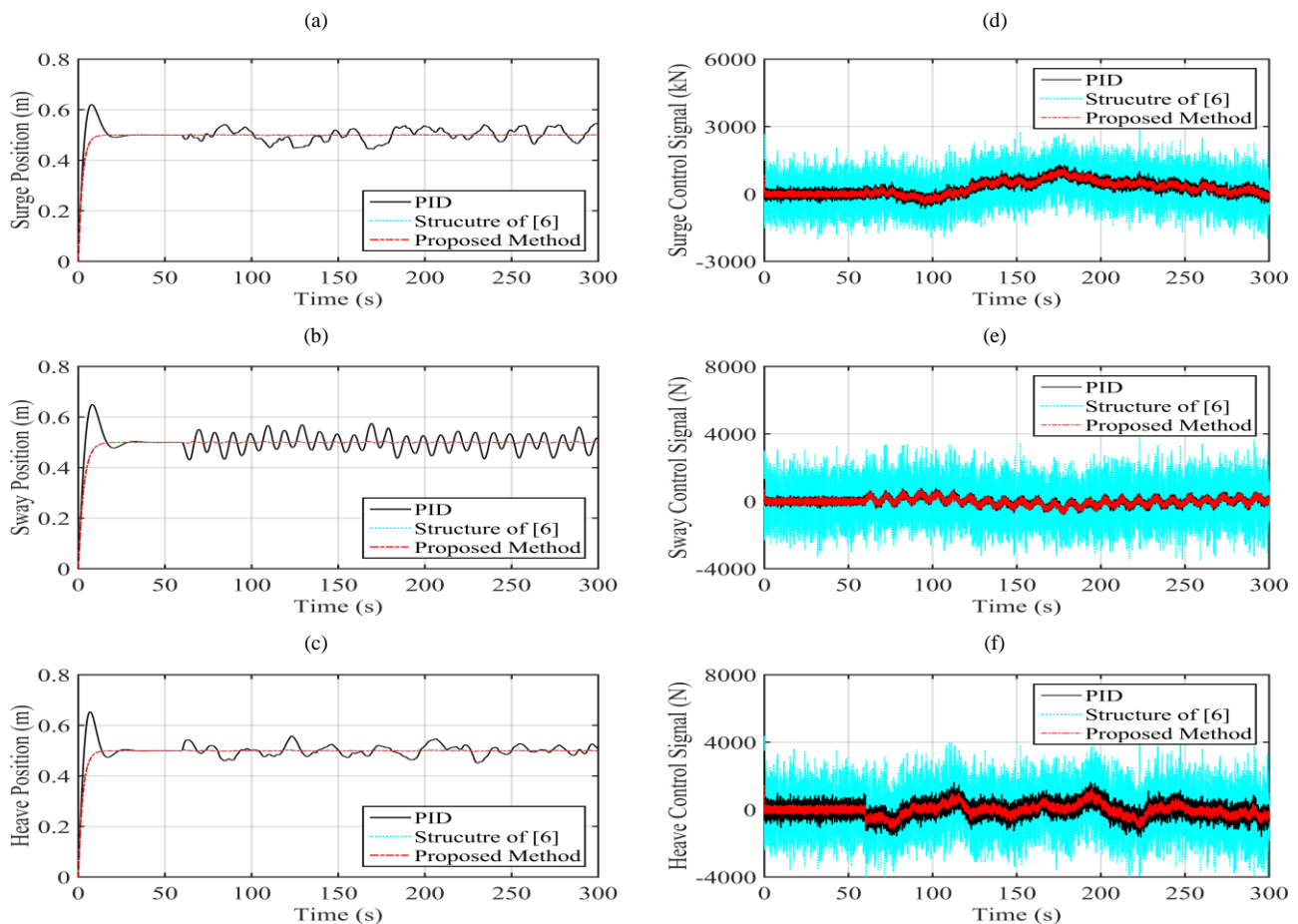


Figure 5. Simulation result for comparing the performance of different control methods in the presence of position sensor noise; (a)-(c): Position, (d)-(f): Control signal.

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