DESIGN OF INERTIAL DELAY OBSERVER BASED MODEL FOLLOWING DYNAMIC SLIDING MODE CONTROL

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Abstract

This paper proposes the design and implementation of Inertial delay observer (IDO) based model following dynamic sliding mode control (DSMC). The Inertial delay observer estimates the states as well as the uncertainties and disturbances in an integrated manner. The DSMC is provides smooth control signal with the mechanism of chattering elimination while maintaining the accuracy of control. The efficacy of the proposed technique is demonstrated with numerical simulation of uncertain second order system. The observer based model following DSMC technique is also validated through experimentation on Quanser DC servo motor. Results show the effectiveness of the combination of the controller-observer design for position control of DC motor against uncertainties and sensor noise. The technique is robust due to appropriate estimation and follows the model precisely which improves overall life of the system. The stability of the designed observer based control scheme is provided by Lyapunov theory.

Keywords: Dynamic sliding mode control, Inertial delay observer, DC servo motor, Lyapunov theory

1. Introduction

The purpose of design of model following control is to generate control such that the controlled system behaves like a model, which specifies the design objectives. It has the objective to minimize the error between the states of the model and the controlled plant despite presence of uncertanity, disturbances and measurement noise. The design guarantees that the error between the states of the model and the controlled plant goes to zero. Over the past decades many model following approches are designed, for controlling the output close to the model output and to satisfy the closed-loop stability as well as regulation. [1, 2, 3, 4, 5].

SMC is a robust control technique to counter the presence of uncertainties and disturbances in the system. But the main drawback of the SMC is that it uses the discontinuous control to achieve the control objective. Thus chattering in the SMC restricts it for the real life applications. SMC requires that, the full state vector to be available for the control to apply effectively. But states may not be available always. The range of uncertainty, if it can not be determined or not known exactly, sliding condition may not be satisfied. Various methods have been proposed to eliminate the chattering like continuous approximation by boundary layer technique[6], to use higher order sliding mode control (HOSM) [7]. Dynamic sliding mode control (DSMC) is also designed for chattering elimination, where the control developed by sliding mode is filtered and then applied to the actual plant [8].

The DSMC adopts a special control structure, in which a integrator as a filter is placed in front of the system as depicted in figure(1). A sliding mode control w is designed for the augmented system consist of system and the filter. Being a sliding mode control, the auxiliary control signal w has chattering, however the actual control signal u, applied to the system is smooth. Here, a low pass filter eliminates the chattering along with maintaining the control accuracy. In case of a system where measurement noise is present DSMC effectively filter out the chattering due to it. Hence, the mechanism of chattering elimination but with maintaining the accuracy of control, both are decoupled in the design of DSMC. [9, 10, 11].

In the design of DSMC, the main problem is to form the sliding surface, as we are designing the SMC for the augmented system, sliding surface should be the function of the states of the augmented system not the actual system. Since the augmented system is one dimension larger than the original system, the new sliding variable in DSMC contains an uncertainty term due to the external disturbance and/or parametric uncertainty. And also from the structure of DSMC one can observe that the lumped uncertainty involves in the augmented system. Evaluation of the new sliding variable in DSMC becomes difficult because of this reason. To over come the problem of bounds of uncertainty, instead of using the bounds of uncertainty in the control one can estimate the uncertainty and disturbance in the system by using the methods like time delay control(TDC), inertial delay control(IDC) and can use it in the control design. Hence, there is a need to design an observer to estimate the lumped uncertainty for the design of sliding surface in DSMC. Different types of state observers are developed to estimate the states as well as uncertainties in the systems like uncertanity and disturbance estimator(UDE), supertwisting disturbance observer(STDO), inertial delay observer(IDO), extended state observer(ESO) etc. [12, 13, 14, 15].

In this paper inertial delay observer (IDO) based model following control is designed. Here the states estimation is achieved by linear observer while uncertainties are estimated by inertial delay method. The proposed strategy estimatate the states as well as the lumped uncertainty in the system. This state and uncertainty observers are more useful for the control design in real time applications where it is difficult to measure all the states using the sensors. The control strategy is verified by the practical experimentation on Quanser's servo plant SRV02 under influence of sensor measurement noise and uncertanities in terms of unmodeled dynamics. The main contributions of the work are summarized as follows:

- Design of model following DSMC by state estimation using IDO for achieving smooth control.
- The effectiveness of the designed controller is verified by simulation of uncertain plant.
- Due to simultaneous estimation of states and uncertainty, IDO based model following DSMC design reduces the need sensors.
- Experimental results validates the efficacy of robustness of control strategies against the presence of disturbance, uncertainties in the system parameters and sensor noise.

The paper is organised as follows. Sect. 2 presents the mathematical model of system. Sect. 3 presents the observer based design approach with numerical simulation. Sect. 4 contains stability analysis. Application of the proposed strategy in Sect. 3 to the system mentioned in Sect. 2 along with the experimental results and perfomance analysis is presented in Sect. 5. Finally in Sect. 6 paper is concluded.

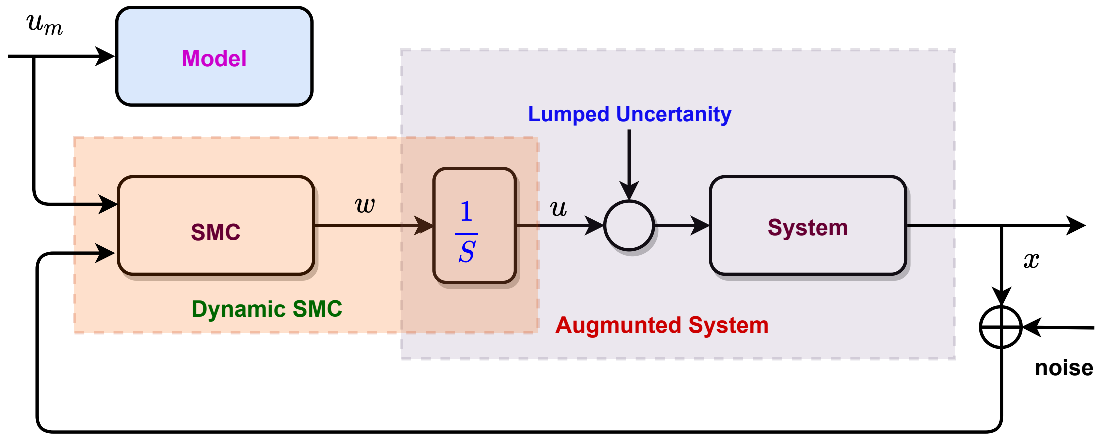


Figure 1: *Model following DSMC design with measurement noise*

2. Mathematical Modelling

Due to excellent speed control characteristics, the DC motors are used in many industrial applications. The most common device used as an actuator in mechanical control is the DC motor. In Quanser set up it is a base unit for controlling rotary inverted pendulum, double inverted pendulum, 2-dof robot etc. As a result, it becomes necessary to control the amount of electric voltage supplied to the servomotor by continuously detecting the position and speed of shaft. It has attracted researchers and considerable research has been done and several methods are proposed and implemented for it.

2.1. Transfer function representation of SRV-02

The dynamic equations and transfer function of SRV-02 servo plant using first principles is discussed in [16]. The servomotor transfer function is given by ,

$$\frac{\theta_l(s)}{V_m(s)} = \frac{K}{s(s\tau + 1)} \tag{1}$$

where

- $\theta_l(s)$ is Laplace transform of position of load,
- $V_m(s)$ is Laplace transform of input voltage,
- K is the steady state gain,
- τ is the system time constant.

2.2. State space representation of SRV-02

For implementation of the proposed control strategy to servo plant we convert transfer function into the state space form. Considering two states for state space model, θ load shaft position as first state x_1 and $\dot{\theta}$ load shaft speed as second state x_2.

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \theta(s) \\ \dot{\theta}(s) \end{bmatrix} \tag{2}$$

The equation (1) is represented in system state variable form as becomes

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -(1/\tau) \end{bmatrix} \tag{3}$$

Input matrix is form as

$$B = \begin{bmatrix} 0 \\ K/\tau \end{bmatrix} \tag{4}$$

while ouput matrix come as

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{5}$$

The output matrix is represented as,

$$y = C \begin{bmatrix} \theta(s) \\ \dot{\theta}(s) \end{bmatrix} \tag{6}$$

We are measuring the position of the load shaft x_1 The design specifications and parameters for the model are considered from [17].

3. Problem formulation

In the design of DSMC, as the lumped uncertainties are included in between the filter and the system, the sliding surface requires the unknown lumped uncertainty in its design. Hence design of sliding surface in DSMC is a tedious and requires the unknown parameter called lumped uncertainty. Therefore it is required to design an observer for estimation of lumped uncertainty for the design of sliding surface. For the systems where the states are unavailable for measurement, there is a need to design an observer which estimates the states of the systems. The main motivation for the simultaneous estimation of states and uncertainty is to reduce the number of sensors and to robustify the control in the presence disturbance. To overcome the problem of bounds of uncertainty, instead of using the bounds of uncertainty in the control one can estimate the uncertainty and disturbance in the system by using IDO and can use it in the control design. The IDO based model following DSMC is designed for experimentation as follows.

3.1. Design of inertial delay observer based model following dynamic sliding mode control

In the real time applications, it is complicated to measure all the states except the output. Here the design of model following DSMC by estimating the system states is proposed. Since the design of sliding surface requires the lumped uncertainty in the system, and here in addition to that system states are also required. Hence, IDO is proposed for estimation of the system states as well as the uncertainty.
Consider the DSMC design for linear time invariant uncertain system with relative degree two

$$\begin{aligned} \dot{x} &= Ax + Bu + Be \\ y &= Cx \end{aligned}$$

The model to be followed is,

$$\begin{aligned} \dot{x}_m &= A_m x_m + B_m u_m \\ y_m &= C x_m \end{aligned}$$

The objective is to design control u so as force the system to follow the sliding dispite of the parameter variations. The design of DSMC by estimating the system states where all states other than output are not available.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Be(x, u, t) \\ y(t) &= Cx(t) \end{aligned} \tag{7}$$

Where, $x \in \Re^n$ is the state vector, $u \in \Re^m$ is the control input and $y \in \Re^p$ is the output of the system. $e(x, u, t)$ is lumped uncertainties which includes uncertainty in A matrix, B matrix and disturbances. The output and input of the system are measurable (available) for all the time $t = 0$. The current state and initial state $x(0)$ are supposed to be non available. $d(x, t)$ is external unmeasurable disturbances.

Assumption:

- Uncertainties of the system and input matrices are lumped into the $e(x, u, t)$
- Lumped uncertainty varies slowly $\dot{e}(x, u, t) \cong 0$.
- The model parameters are completely known and no uncertainty or disturbances in the model
- The model matrices A_m and B_m are stable.

Inertial delay observer for the estimation of states of the system is given as,

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) + B\hat{e}(x, u, t) + L(y(t) - \hat{y}(t)) \\ \hat{y}(t) &= C\hat{x}(t) \end{aligned} \tag{8}$$

Where, L is observer gain matrix, $\hat{e}(x, u, t)$ is estimation of lumped uncertanity $\hat{x}(t)$, $\hat{y}(t)$ are states and output of observer respectively

From eqn.(7), we get,

$$Be(x, u, t) = \dot{x}(t) - Ax(t) - Bu(t) \tag{9}$$

Defining the pseudo inverse of matrix B as,

$B^+ = (B^T B)^{-1} B^T$, then the equation (7) is,

$$e(x, u, t) = B^+[\dot{x}(t) - Ax(t) - Bu(t)] \tag{10}$$

If all the states are available for measurement then one can directly use above eqn (10) for estmation but, all the states are not available so replacing $x(t)$ with $\hat{x}(t)$ in eqn. (10) which give us,

$$\tilde{e}(x, u, t) = B^+[\dot{\hat{x}}(t) - A\hat{x}(t) - Bu(t)] \tag{11}$$

uncertanity can be estimated as,

$$\hat{e}(x, u, t) = G_f(s)\ e(x, u, t) \tag{12}$$

$$G_f(s) = \frac{1}{\tau s + 1} \tag{13}$$

where $G_f(s)$ is first order filter with high bandwidth. Note that, for sake of simplicity, the laplace domain notations are used to represent $G_f(s)$ in the time domain equations.

$$\hat{e}(x, u, t) = B^+[\dot{x}(t) - Ax(t) - Bu(t)]G_f(s) \tag{14}$$

Using equations (8) and (11) and simplifying

$$\begin{aligned} \hat{e}(x, u, t) &= B^+[A\hat{x}(t) + Bu(t) + B\hat{e}(x, u, t) + L(y(t) - \hat{y}(t)) - A\hat{x}(t) - Bu(t)]G_f(s) \\ &= B^+ LC\tilde{x}(t)\frac{G_f(s))}{1 - G_f(s)} \\ &= \frac{B^+ LC\tilde{x}(t)}{\tau s} \end{aligned} \tag{15}$$

$$\dot{\hat{e}}(x, u, t)) = -\frac{1}{\tau} B^+ LC\tilde{x}(t) \tag{16}$$

Observer error dynamics is derived as,

$$\dot{\tilde{e}}(x,u,t)) = -\frac{1}{\tau}B^{+}LC\tilde{x}(t) - \dot{\hat{e}}(x,u,t) \tag{17}$$

We assumed that the uncertainties varies slowly,
$\dot{\tilde{e}}(x,u,t)) \cong 0$, considering it equation(17) becomes,

$$\dot{\tilde{e}}(x,u,t) = -\frac{1}{\tau}B^{+}L\tilde{x}(t) \tag{18}$$

In combined form we can write observer dynamics (as matrix form)

$$\begin{bmatrix} \dot{\tilde{x}}(t) \\ \dot{\tilde{e}}(x,u,t) \end{bmatrix} = \begin{bmatrix} A - LC & B \\ -\frac{1}{\tau}B^{+}LC & 0 \end{bmatrix} \cdot \begin{bmatrix} \tilde{x}(t) \\ \tilde{e}(x,u,t) \end{bmatrix} \tag{19}$$

Converting this matrix form into the form which is similar to the pole placement problem. Using closed loop poles of overall system at desired location,

$H = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}$, $G = \begin{bmatrix} C & 0 \end{bmatrix}$ and $K_{ob} = \begin{bmatrix} L \\ \frac{1}{\tau}B^{+}L \end{bmatrix}$

The eigen values of the matrix $A - K_{ob}G$ can be made arbitrary by appropriate choice of the observer gain K_{ob}, when the pair (H, G) is observable.

3.2. Sliding surface

Now in model following, one can consider the sliding surface as the error between the model and actual system. So that when ever sliding surface becomes zero the system should follow the model. Taking this idea as a backend sliding surface is chosen as

$$\sigma = y_e^{''} + \lambda_1 y_e^{'} + \lambda_0 y_e \tag{20}$$

Where y_e, y_e', y_e'' are the errors of outputs and its derivatives between system and model

$$\begin{aligned} y_e &= Cx - Cx_m \\ y_e' &= CAx - CA_m x_m \\ y_e'' &= CA^2x + CABu + CABe - CA_m^2 x_m - CA_m B_m u_m \end{aligned} \tag{21}$$

From the inertial delay observer one can get the estimate of the states $\hat{x}$ and lumped uncertainty $\hat{e}$. Here SMC is designed for the augmented system, so one can choose the sliding surface for the model following as,

$$\hat{\sigma} = \hat{y_e}'' + \lambda_1 y_e' + \lambda_0 y_e \tag{22}$$

The y_e, y_e', y_e'' can be defined by using estimated states as,

$$\begin{aligned} y_e &= Cx - Cx_m \\ y_e' &= CA\hat{x} - CA_m x_m \\ y_e'' &= CA^2\hat{x} + CABu + CAB\hat{e} - CA_m^2 x_m - CA_m B_m u_m \end{aligned} \tag{23}$$

3.3. Control design

The control for the actual plant can be obtained from the auxiliary control as,

$$u = \int w \, dx \tag{24}$$

Sliding surface is designed for the model following DSMC, From the equation (22) and taking it's derivative one can get,

$$\dot{\hat{\sigma}} = CA^3\hat{x} + CA^2Bu + CABw - CA_m^3x_m - CA_m^2B_mu_m + CA_mB_m\dot{u}_m + \hat{e}^* + \lambda_1\hat{y_e}'' + \lambda_0 y_e' \quad (25)$$

where, $\hat{e}^* = CA^2B\hat{e} + CAB\dot{\hat{e}}$
Assume the auxiliary control w as

$$w = w_{eq} + w_n \quad (26)$$

where w_{eq} addresses the known dynamics while w_n is for the unknown dynamics. Then, the for known dynamics w_{eq} is selected as,

$$\begin{aligned} w_{eq} = &-(CAB)^{-1}(CA^3\hat{x} + CA^2Bu + CABw - CA_m^3x_m - CA_m^2B_mu_m - CA_mB_m\dot{u}_m + \hat{e}^* \\ &+ \lambda_1\hat{y_e}'' + \lambda_0 y_e' + K\hat{\sigma}) \end{aligned} \quad (27)$$

where k is a small positive constant.
To satsisfy sliding condition the control w_n is selected as,

$$w_n = -(CAB)^{-1}K_1 sign(\hat{\sigma}) \quad (28)$$

where, $K1$ is a positive constant $> |\tilde{e}^*|$.

3.4. Numerical simulation

To demonstrate the efficacy of the design of IDO based model following DSMC with state estimation, a second order system is considered. The system matrices are as follows,

$$A = \begin{bmatrix} 0 & 1 \\ -3 & -4 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

The reference model to be followed is

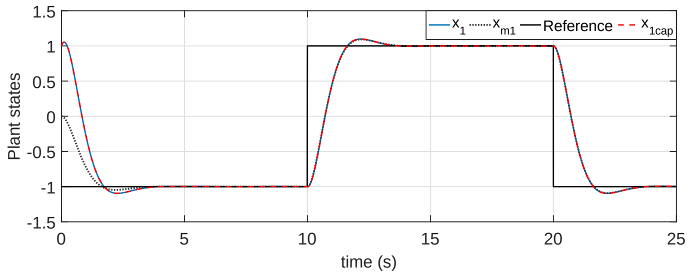
$$A_m = \begin{bmatrix} 0 & 1 \\ -4 & -2.8 \end{bmatrix}, \quad B_m = \begin{bmatrix} 0 \\ 4 \end{bmatrix}$$

Initial conditions are

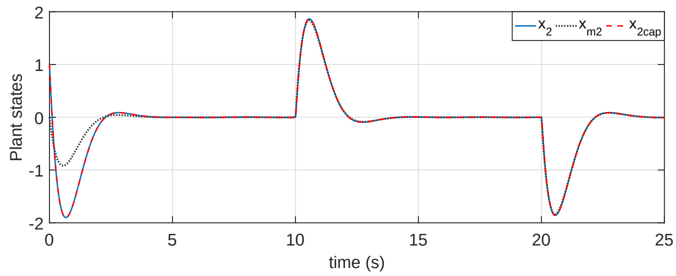
$$x(0) = \begin{bmatrix} 1 & 1 \end{bmatrix}^T, x_m(0) = \begin{bmatrix} 0 & 0 \end{bmatrix}^T$$

With the 40% uncertainties in the system parameters and $sin(2t)$ as a external disturbance. while the low pass filter time constant $tau = 0.01$, the constant parameters are $\lambda_0 = 15$, $\lambda_1 = 5$, $K = 5$ and $K_1 = 10$. The observer pols are at $\begin{bmatrix} -5 & -9 & -11 \end{bmatrix}^T$. Apart from the disturbance here uniform measurement noise of absolute magnitude 0.01 is added with the lumped uncertainty. The reference input u_m is square wave switching at $10s$.

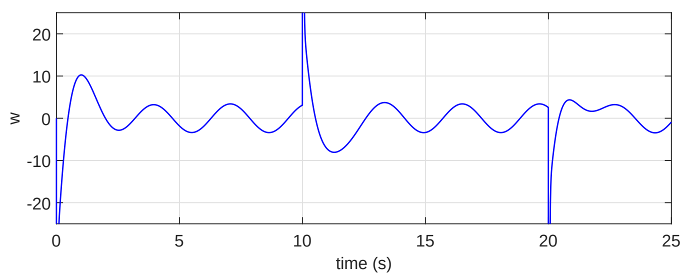
The states of the system are estimated using the IDO and accuracy of the estimation depends on the observer poles. The observer poles are selected such that, it estimates the states and the uncertainty precisely. The simulation results in Fig. (2) depicts that, system is following the model precisely despite the presence of uncertanities, disturbance and noise. The plot of plant and observer states are as shown in Fig.(2a) and (2b). The Fig. (2c) shows auxiliary control w, designed for the augmented system, while the actual control u to the system is smooth as shown in Fig.(2d). Finaly the sliding surface is in Fig.(2e).



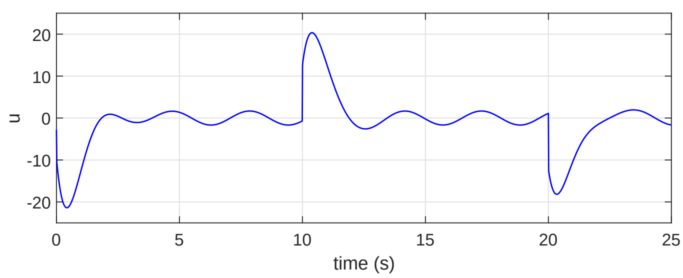
(a) *State, it's estimate and observer state* x_1



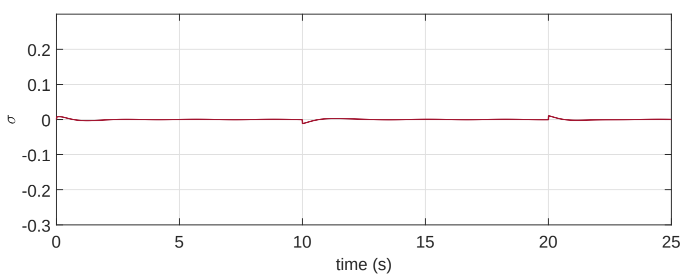
(b) *State it's estimate and observer state* x_2



(c) *Auxiallary control* w



(d) *Control* u



(e) *Sliding surface* σ

Figure 2: *IDO based model following DSMC control of a uncertain plant.*

4. Stability analysis

The model is considered to be stable by design so for the designed control, stability of the system is proved. Consider the Lyapunov function as,

$$V = \frac{1}{2}\sigma^2 \tag{29}$$

Taking derivative we get,

$$\dot{V} = \sigma\dot{\sigma} \tag{30}$$

From the equation(21)

$$\begin{aligned}\dot{\sigma} =& CA^3x + CA^2Bu + CA^2Be + CABw + CAB\dot{e} \\ &+ \lambda_1 y'' + \lambda_0 y'\end{aligned} \tag{31}$$

During sliding motion, the control term w_{eq} substituting in the equation(31) we get,

$$\begin{aligned}\dot{\sigma} =& CA^3\tilde{x} + CA^2B\tilde{e} + CAB\dot{\tilde{e}} + \lambda_1\tilde{y}'' + \lambda_0\tilde{y}' - K\hat{\sigma} \\ &+ CABw_n\end{aligned} \tag{32}$$

The observer error $\tilde{x}$ in equation (19) converges to zero asymptotically, if K_{ob} is chosen appropriatly. Then, $\dot{\sigma}$ is,

$$\dot{\sigma} = CABw_n - K\hat{\sigma} + \tilde{e}^* \tag{33}$$

So the equation (30) becomes,

$$\begin{aligned}\dot{V} =& \sigma\tilde{e}^* - K\sigma\hat{\sigma} - \sigma CAB(CAB)^{-1}K_1 sign(\hat{\sigma}) \\ \dot{V} =& \sigma\tilde{e}^* - K\sigma\hat{\sigma} - \sigma K_1\frac{|\hat{\sigma}|}{\hat{\sigma}} \\ \dot{V} \leq& |\sigma|\left(|\tilde{e}^*| - K|\hat{\sigma}| - K_1\frac{|\hat{\sigma}|}{|\hat{\sigma}|}\right) \\ \dot{V} \leq& |\sigma|\left(|\tilde{e}^*| - K|\hat{\sigma}| - K_1\right)\end{aligned} \tag{34}$$

As $K_1 > |\tilde{e}^*|$,
K_1 and K are both positive constants, $\dot{V}$ is negative definite.
Thus the sliding manifold is stable.

5. Application of IDO based model following DSMC control for position control of DC servomotor

The real time implementation of the model following DSMC strategy discussed in Sect. 3 has been done for position control of the Quanser servomotor SRV02. The block diagram of IDO based model following DSMC control of the servomotor is as shown in Fig.(3). It has potentiometer, encoder and tachometer. The potentiometer and encoder sensors measures the angular position of the load gear and tachometer is used to measure its velocity. The different parameters of DC servomotor are considered as mentioned in Quanser setup manual [17]. The constant parameters are $\lambda_0 = 15$, $\lambda_1 = 7$, $K = 1$ and $K_1 = 20$. Here uniform measurement noise as a sensor noise of absolute magnitude 0.01 is added. The observer poles are selected at $1.5 * [-5\ -9\ -11]$. The inital condition for states are considered as $[0\ \ 0]^T$ and $[1\ \ 1]^T$ respectively for the consideration.

Experimentation has done under different considerations like with and without noise for the observer based model following DSMC strategy. Fig.(4), (5) shows the system and model states where the initial mismatch is due to the initial conditions of the model and system. The experimental results have proved the efficacy of proposed design for real time position control of DC motor.

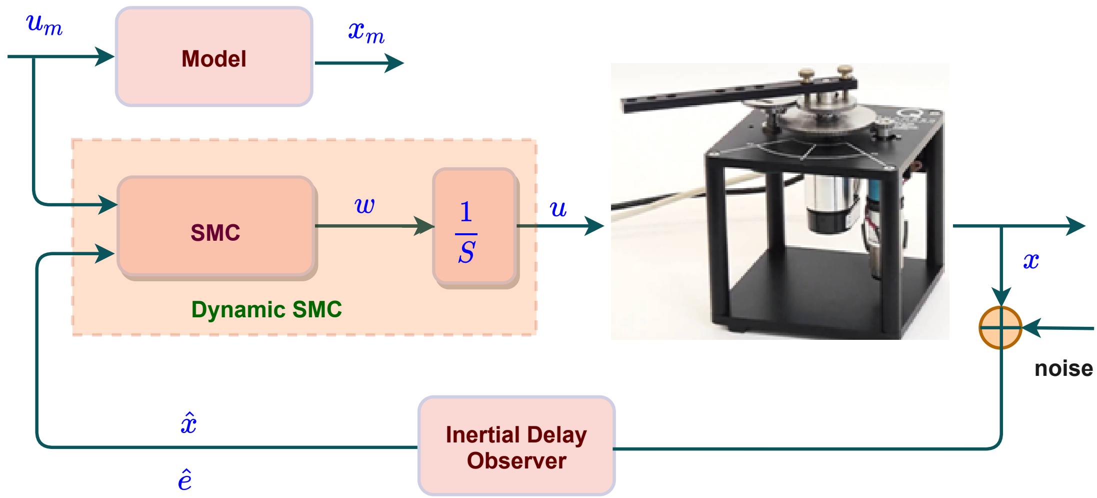


Figure 3: *IDO based model following dynamic sliding mode control of DC servomotor with measurement noise*

The effectiveness of the scheme is assessed through the results shown in Fig. (4) are taken from the encoder for output without any measuring noise. Fig.(4a) and Fig.(4b) shows the states of the model, system and observer, where one can observe that the observer has followed the model dynamics as the estimation is accurate. Fig.(4c) shows the chattering in the auxiliary control w while the actual control to the system u is smooth control shown in Fig.(4d). The sliding surface σ is shown in Fig. (4e).

IDO based DSMC design estimates the states and uncertainty simultaneously, It reduces reduces the need of sensors. In order to demonstrate robustness of the controller, the noisy output is taken from the potentiometer that is the control is tested for the system with measurement noise and uncertainty. The results are shown in Fig.(5a). As the output from the potentiometer is noisy, the second state calculated consists heavy chattering due to the addition of measurement noise as shown in Fig. (5b), model and the observer states are smooth at the same time. Due to it, the auxiliary control is affected as shown in Fig.(5c) but the actual control driving the system is smooth signal as shown in Fig.(5d). The sliding surface σ is shown in Fig. (5e). With the design of DSMC the actual system is driven by the smooth control though the states are contaminated with the measurement noise.

6. Conclusion

In this paper, performance analysis of observer based estimation based techniques has been carried out for position control of DC motor. The effectiveness of the proposed schemes has been validated in presence of uncertainty due to unmodeled dynamics and disturbance along with measurement noise. DSMC is made more robust by augmenting a observer. IDO based model following DSMC estimates the system states as well as the uncertainty. Due to the simultaneous estimation of states and uncertainty, it reduce the number of sensors and robustify the control despite unknown disturbance and uncertainties in the system parameters or load changes. The simulation and experimental results show that the proposed IDO based model following DSMC is robust and follows the model precisely. The essential boundness of lumped uncertainty estimation error and sliding manifold is demonstrated by Lyapunov theory.

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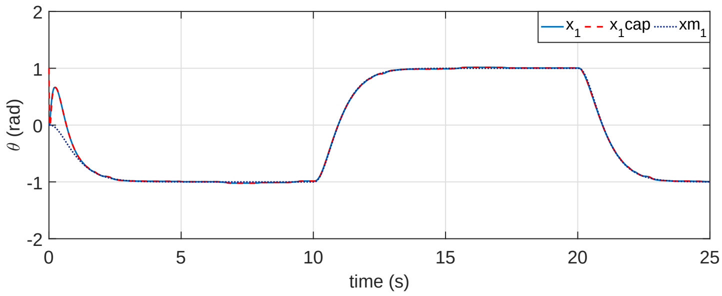
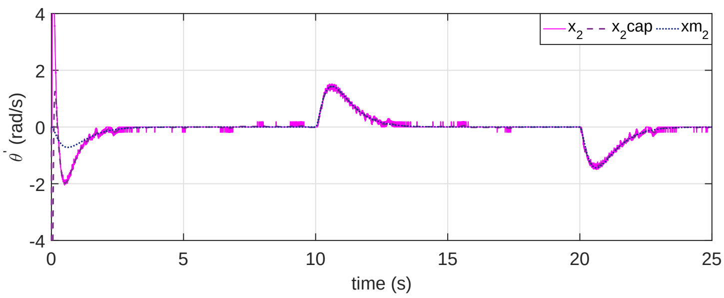
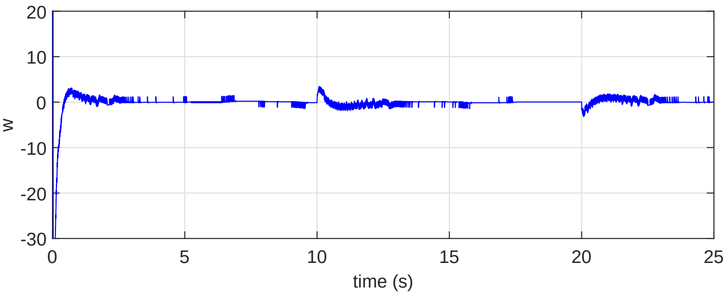


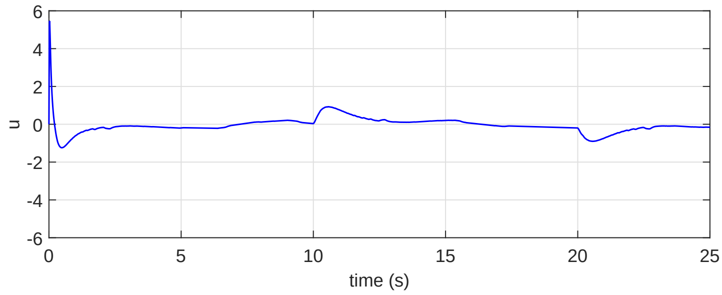
(a) *Actual position of shaft and its estmation: state x_1*



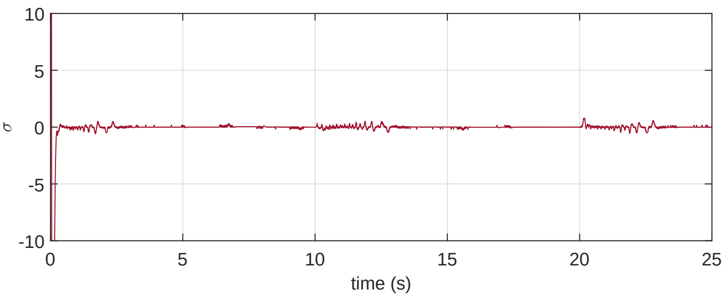
(b) *Actual speed of shaft and its estmate: state x_2*



(c) *Auxiallary control w*

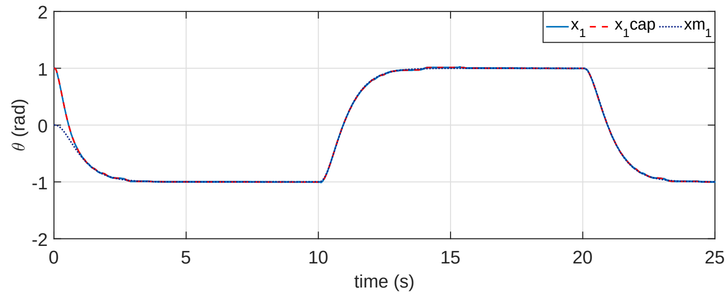


(d) *Control u*

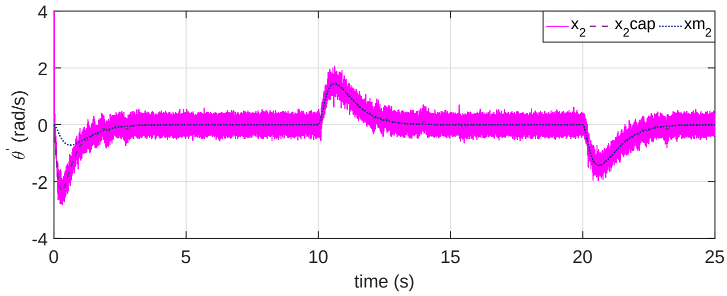


(e) *Sliding surface σ*

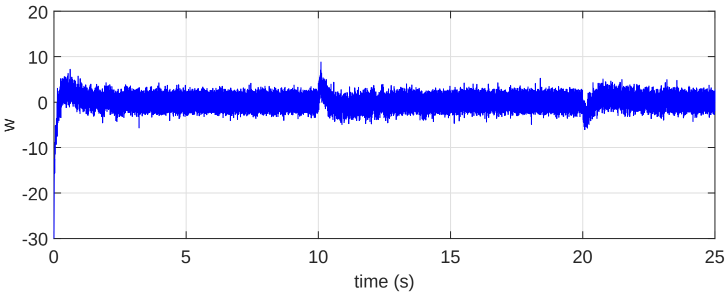
Figure 4: *IDO based model following DSMC control of DC servomotor without measuring noise.*



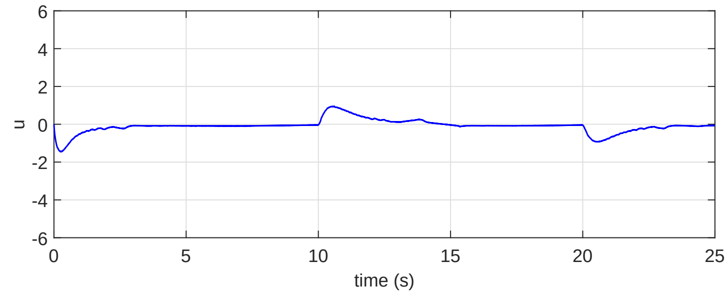
(a) *Actual position of shaft and its estmation: state* x_1



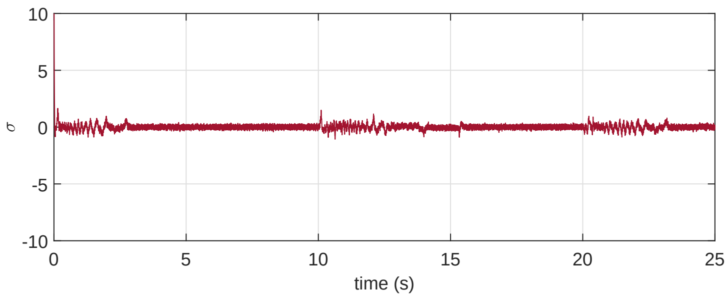
(b) *Actual speed of shaft and its estmate: state* x_2



(c) *Auxiallary control* w



(d) *Control* u



(e) *Sliding surface* σ

Figure 5: *IDO based model following DSMC control of DC servomotor with measuring noise.*