Novel Observers for Compensation of Communication Delay in Bilateral Control Systems

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***Abstract*—The problem of communication delay in bilateral or teleoperation systems is even more emphasized with the use of the internet for communication, which may give rise to loss of transparency and even instability. To address the problem, numerous methods have been proposed. This study is among the few recent studies taking a disturbance observer approach to the problem of time delay, and introduces a novel sliding-mode observer to overcome specifically the effects of communication delay in the feedback loop. The observer operates in combination with a PD+ controller which controls the system dynamics, while also compensating load torque uncertainties on the slave side. To this aim, an EKF based load estimation algorithm is performed on the slave side. The performance of this approach is tested with computer simulations for the teleoperation of a 1-DOF robotic arm. The simulations reveal an acceptable amount of accuracy and transparency between the estimated slave and actual slave position under both constant and random measurement delay and variable and step-type load variations on the slave side, motivating the use of the approach for internet-based bilateral control systems.**

Keywords: teleoperation, bilateral systems, communication delay, disturbance observer, sliding-mode observer, EKF.

I. Introduction

Teleoperation and bilateral control systems have been attracting a lot of interest due to the potential of many interesting applications to enhance human life; i.e telesurgery, telerobotics for hazardous tasks and environments etc. However, an important factor affecting the performance of such systems is communication delays, which occur in the delivery of the control command to the slave side as well as the delivery of the feedback signal from slave to the master through a communication channel. The problem is even more emphasized with the use of the internet as the communication media, giving rise to instability and loss of transparency.

In this paper, the communication delay in the delivery of the control input to the slave side is addressed as *control delay*, while the delay in the delivery of the feedback signal to the master side is addressed as the *measurement delay*, the compensation of which is the primary aim of this paper.

There have been numerous studies on the compensation of time delay; early research used the wave variable transformation approach to solve for constant time delay [1]. Wave variable approach was integrated with different methods and algorithms to address the problem of variable time delay [2], [3]. Some other methods to tackle the problem of time delay are impedance shaping [4], fuzzy logic [5], μ - synthesis and H_∞-optimal control [6], and Smith-predictor technique [7], [8].

Another recent approach is the consideration of the communication delay (combining control and measurement delays) as a disturbance, thereby taking a disturbance observer approach to solve the problem, using a communication delay observer (CDOB) as in [9] and [10]. The method has been shown to be more effective than the Smith-predictor approach due to its independence on modeling errors and capability to handle variable delays as expected with the internet [11], [12]. In this approach, the system stability and performance is totally dependent on the cutoff frequency, g, of the low pass filter of the CDOB, which is determined off-line based on given system and controller parameters. It has also been shown that with the proper choice of this frequency, the DOB can handle load torque and inertial uncertainties successfully. Additionally, the authors interpret the offset in the steady state (under no delay condition) to be caused by the unknown slave parameters. This is expected and should be addressed.

This study presents a different control and estimation approach which is also based on the consideration of time delay as a disturbance. A sliding-mode(SM) based novel disturbance observer is developed to deal with the communication delay problem using a master- slave configuration where the main control and evaluation of the feedback is performed on the master side, while load compensation is performed on the slave side. Two observers are designed to this aim; namely, the SM based observer estimating the slave position on the master side and an EKF observer to estimate load torque and parameter variations on the slave side. Hence, different from the above mentioned CDOB approach, in this study, there is no need for any *a priori* information on either the system or controller parameters, and the requirement of the SM observer for accurate load/system parameters information is thus met. The control of the slave is performed through a PD+ controller, which takes the estimated slave information on the states from the SM observer, and slave load and parameter information from the EKF observer to further cancel load and friction effects on the slave side.

The evaluation of the proposed observer-controller pair is performed with computer simulations for a step-type reference trajectory under constant and random measurement and control delays. Tests are also conducted for both step type and sinusoidal load variations on the slave side.

The organization of the paper is as follows. In Section II: the theory behind SMO and EKF based disturbance observer is discussed. Simulation results for different conditions and parameter settings are presented in Section III and conclusions in Section IV.

II. Development Of SM And EKF Observer

A. Design of SM Observer

The system to be controlled on the slave side is 1-DOF arm operating under gravity effect. The control system in consideration is a PD+ controller located on the master side. Hence, the first step is the design of an observer that will estimate the actual slave position and velocity in spite of the delay in the feedback loop. The well-known system model is as follows:

$$\begin{aligned}\dot{\theta}(t) &= \omega(t)\\ \dot{\omega}(t) &= \frac{K_t}{J}u(t) - \frac{B}{J}\omega(t) - \frac{T_L}{J}\end{aligned} \tag{2.1}$$

where K_t is torque constant (N-m/A),

J is effective slave inertia (kg-m^2),

B is effective viscous friction (N-m s/rad),

$\theta(t)$ is system angular position output (rad),

$\omega(t)$ is system angular velocity output (rad/s),

$u(t)$ is control input of the system,

T_L is load torque on the slave side. (N-m).

As a different observer will estimate the load torque, $T_L = 0$ in the derivation of the SM observer. Hence,

$$\dot{\omega}(t) = \frac{K_t}{J}u(t) - \frac{B}{J}\omega(t). \tag{2.2}$$

The observer model is taken in the following form:

$$\begin{aligned}\dot{\theta}_1(t) &= \omega_1(t)\\ \dot{\omega}_1(t) &= \frac{K_t}{J}u(t) - \frac{B}{J}\omega_e(t) + u_{o1}(t)\end{aligned} \tag{2.3}$$

where $\theta_1(t)$ is intermediate angular position output (rad),

$\omega_1(t)$ is intermediate angular velocity output (rad/s),

$\omega_e(t)$ is estimated angular velocity output (rad/s),

$u_{o1}(t)$ is control input of the observer.

The estimated states could be represented as,

$$\begin{aligned}\dot{\theta}_e(t) &= \omega_e(t)\\ \dot{\omega}_e(t) &= \dot{\omega}_m(t) - \left[u_{o1}(t)\right]_{eq}\end{aligned} \tag{2.4}$$

where $[u_{o1}(t)]_{eq}$ is equivalent control input of system.

The observer control $u_{o1}(t)$ is designed based on the SMC framework such that the Lyapunov stability conditions are satisfied for the sliding mode manifold $\sigma_1(t) = C_1 e_{\theta 1}(t) + e_{\omega 1}(t)$ where $e_{\theta 1}(t)$, $e_{\omega 1}(t)$ are the estimated position and velocity errors, respectively and are defined in Eq. 2.5 and Eq. 2.6.

$$e_{\theta 1}(t) = \theta_m(t) - \theta_1(t) \tag{2.5}$$

$$e_{\omega 1}(t) = \omega_m(t) - \omega_1(t)\cdot \tag{2.6}$$

A properly selected Lyapunov candidate, $\sigma_1(t)$, will ensure the stability of the observer as it also represents the dynamics of the observer output under parameter and model uncertainties. In other words, with the choice of the SM based observer, the output will be forced to a behavior denoted by $\sigma_1(t)$ regardless of parameter and model uncertainties as long as they satisfy the matching condition.

For a system to be stable according to the Lyapunov stability approach, the system energy should remain non negative until the desired performance is achieved, while its derivative should be negative definite. Therefore, using the Lyapunov stability conditions,

$$V_1(t) = \sigma_1^2(t); \dot{V}_1(t) = \sigma_1(t)\dot{\sigma}_1(t) = -D_1\sigma_1^2(t) \tag{2.7}$$

$$\dot{\sigma}_1(t) = C_1 e_{\omega}(t) + \dot{\omega}_m(t) - \dot{\omega}_1(t). \tag{2.8}$$

The SM control law is thus derived as follows [13]:

$$u_{o1}(k) = u_{o1}(k-1) + \left[\frac{(1 + D_1 T)\sigma_1(k) - \sigma_1(k-1)}{T}\right]. \tag{2.9}$$

The control in Eq. 2.9 will enforce the sliding mode to the manifold $\sigma_1(t) = 0$, so that the equivalent control is determined from $\dot{\sigma}_1(t) = 0$. The equivalent control has the following form:

$$\begin{aligned}[u_{o1}(t)]_{eq} &= C_1 e_{\omega 1}(t) + \dot{\omega}_m(t) - \dot{\omega}_1(t)\\ &= C_1 e_{\omega 1}(t) + \dot{\omega}_m(t) - \frac{K_t}{J}u(t) + \frac{B}{J}\omega_e(t)\cdot\end{aligned} \tag{2.10}$$

From Eq. 2.2, $\frac{K_t}{J}u(t) = \frac{B}{J}\omega(t) + \dot{\omega}(t)$, so Eq. 2.10 becomes,

$$[u_{o1}(t)]_{eq} = C_1 e_{\omega 1}(t) + [\dot{\omega}_m(t) - \omega(t)] + \frac{B}{J}[\omega_e(t) - \omega(t)]\cdot \tag{2.11}$$

From Eq. 2.4, $\left[u_{o1}(t)\right]_{eq} = \dot{\omega}_m(t) - \dot{\omega}_e(t)$, therefore substituting in Eq. 2.11,

$$\left(\dot{\omega}_e(t) - \dot{\omega}(t)\right) + \frac{B}{J}\left(\omega_e(t) - \omega(t)\right) = -C_1 e_{\omega}(t) \tag{2.12}$$

when $\sigma_1(t) \to 0 \Rightarrow e_{\omega 1}(t) \to 0, e_{\theta 1}(t) \to 0$, therefore,

$$\begin{aligned}\omega_e(t) &= \omega(t)\\ \theta_e(t) &= \theta(t).\end{aligned} \tag{2.13}$$

From Eq. 2.13, it can be seen that the system converges eventually, that is, the estimated position and velocity converge to the actual position and velocity of the slave. However, as can be seen from Eq. 2.12, the asymptotic convergence depends on the accurate knowledge of *B* and *J*, which is an issue to be addressed in our next study. Fig. 1 shows the block diagram of the system implemented.

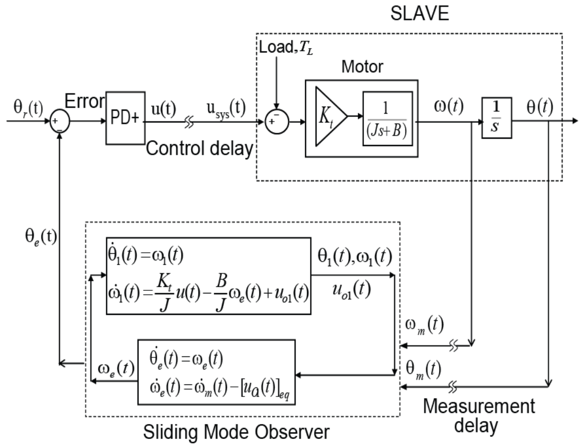


Fig. 1: Block diagram of system with SMO compensating measurement delay.

B Design of EKF Observer

In this section, the design of the EKF based disturbance observer (EKFO) for the slave side of the system will be presented. The system is modeled as,

$$\frac{d\,\omega(t)}{dt} = \frac{k_T}{J}u(t) - \frac{B}{J}\,\omega(t) - \frac{1}{J}d(t) \qquad (2.14)$$

$$\dot{\theta}(t) = \omega(t)\,. \qquad (2.15)$$

With state-space representation,

$$\dot{x}(t) = A\,x(t) + Bu(t) + D(t) \qquad (2.16)$$

$$y(t) = C\,x(t) = \theta(t)\,. \qquad (2.17)$$

where, $A = \begin{bmatrix} -b & 0 \\ 1 & 0 \end{bmatrix}$;

$B = \begin{bmatrix} a \\ 0 \end{bmatrix}$;

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

$D(t) = \begin{bmatrix} -c\,d(t) \\ 0 \end{bmatrix}$.

and $a = \frac{k_T}{J},\ b = \frac{B}{J},\ c = \frac{1}{J}$.

The extended state-space model of the system is given as below:

$$\dot{x}_e(t) = A_e\,x_e(t) + B_e\,u(t) + W(t) \qquad (2.18)$$

$$z(t) = C_e\,x_e(t) + v(t)\,. \qquad (2.19)$$

where *W(t)* is modeling error vector,

v(t) is measurement noise,

$A_e = \begin{bmatrix} -b & 0 & -c \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$;

$B_e = \begin{bmatrix} a \\ 0 \\ 0 \end{bmatrix}$;

$C_e = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$;

$x_e(t) = \begin{bmatrix} \omega(t) \\ \theta(t) \\ d(t) \end{bmatrix}$.

Discretizing the extended system equation, we get,

$$\hat{x}_e(k) = \left(I - T\,A_e\right)\hat{x}_e(k-1) + T\,B_e\,u(k-1) \qquad (2.20)$$

$$\hat{z}(k) = C_e\,\hat{x}_e(k)\,. \qquad (2.21)$$

The EKF equations can be derived as follows [14]:

$$N(k) = F_x\;P(k-1)\,F_x^T + F_u R\,F_u^T \qquad (2.22)$$

$$P(k) = N(k) - N(k)\,H^T H\,N(k)\left[H\,N(k)\,H^T + R\right]^{-1} + Q \qquad (2.23)$$

$$\hat{x}_e(k) = F_x\;\hat{x}_e(k-1) + F_u\;u(k-1) + P(k)\,H^T\,R^{-1}\left[z - H\,\hat{x}_e(k-1)\right]. \qquad (2.24)$$

where $F_x = \left(I - T\,A_e\right)$,

$F_u = T\,B_e$,

$Q = E\{W^T W\}$,

$R = E\{v^T v\}$.

The block diagram of the system including the EKF observer is shown in Fig. 2.

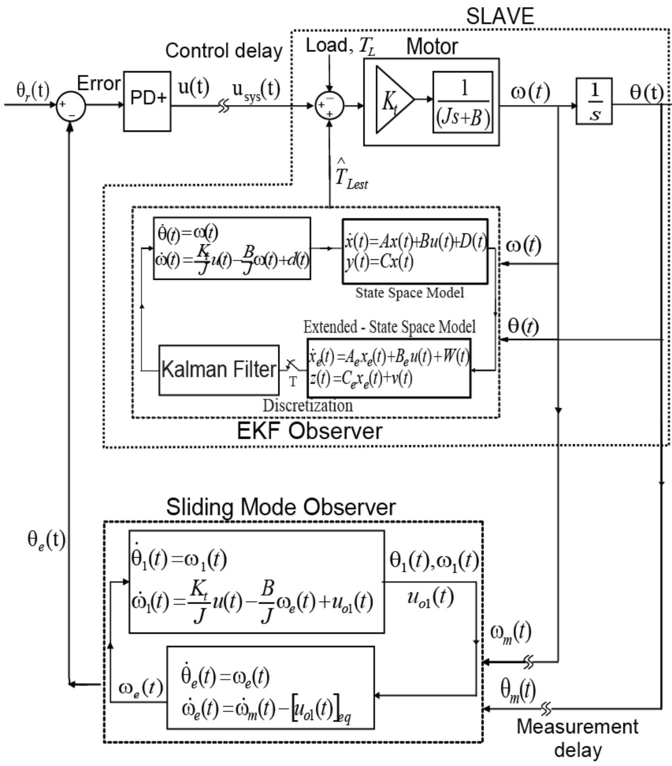
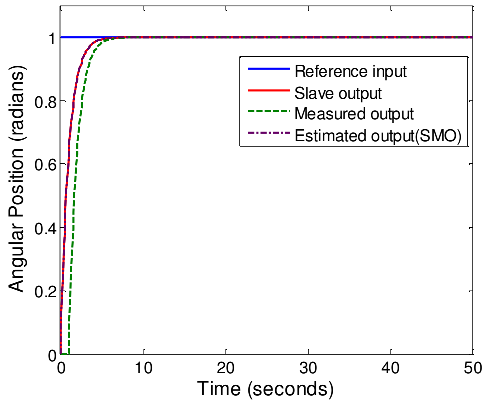


Fig. 2: Block diagram of the full system with PD+, SM and EKF observers.

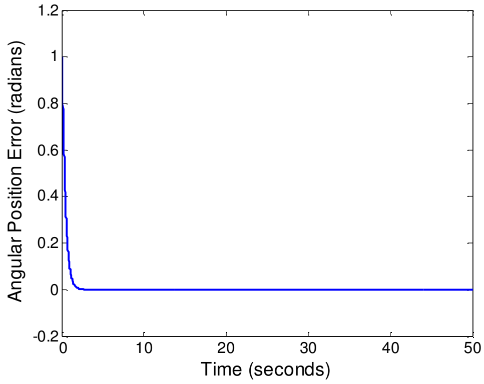
III. Simulation Results

The performance of the system under parameter changes are presented and discussed in this section. Constant delay refers to a delay of 1 second and random delay refers to a delay varying between 1-2 seconds.

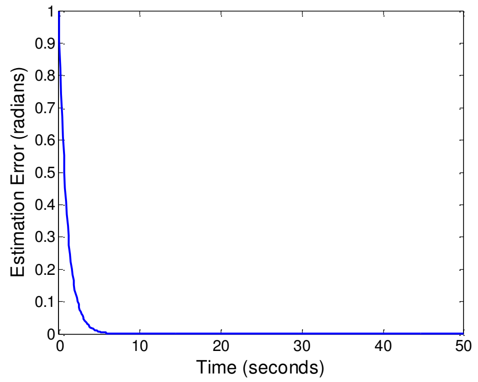
The response of the system under a constant measurement delay with no load is shown in Fig. 3(a). Figs 3(b) and 3(c) show the error between the reference input and system output, and system output and estimated output respectively.



a) Position output.



b) Position error

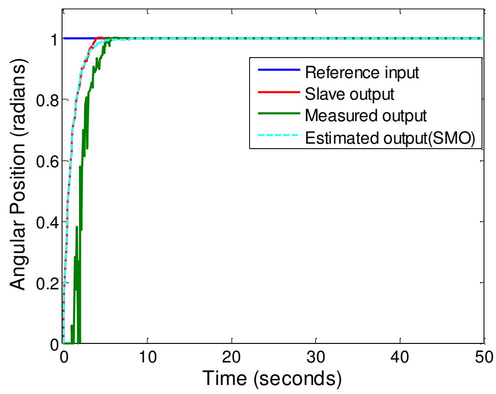


c) Output error

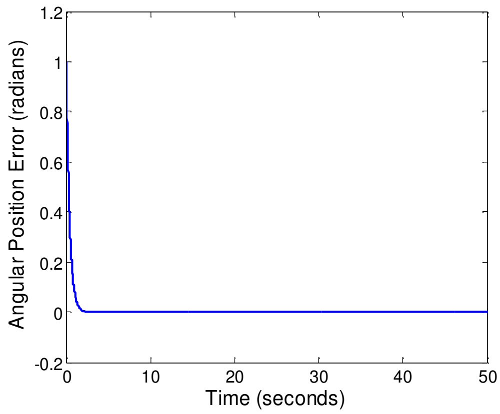
Fig. 3: a) Position output, b) Position error between reference input and system output, c) Position error between system output and estimated output under no load, a constant measurement delay (1 sec) with PD controller.

In Fig. 3(a), the reference input is shown in blue. The output measured at the slave (red) and the estimated value of the output (dotted purple) overlap. This means that there is perfect transparency in the system despite the time delay. This is because the observer estimates the actual slave position accurately, provided the slave model under no load is known accurately, as in this case.

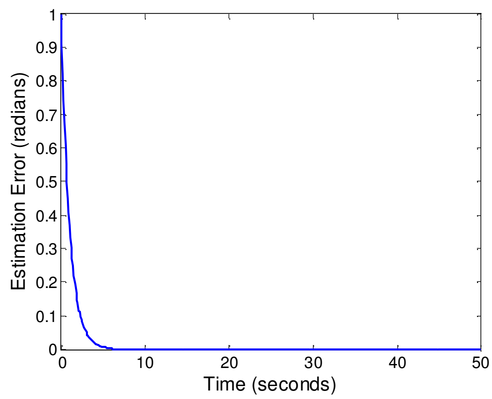
Fig. 4 shows the response of system, under random measurement delay and no load.



a) Position output.



b) Position error



c) Output error

Fig. 4: a) Position output, b) Position error between reference input and system output, c) Position error between system output and estimated output under no load, a random measurement delay (1-2 sec) with PD controller.

In Fig. 4(a), the reference input is shown in blue. The slave output (red) and the estimated output (cyan) mostly overlap. The fluctuations on the measured signal (green) are due to the measurement delay oscillating between 1 and 2 sec. The angular position error and estimation error are shown in (b) and (c), respectively.

With the application of an unknown and uncompensated load on the slave side, the system becomes unstable. In this study, a solution is proposed for this problem as well as measurement delay.

To compensate for the load, PD+ controller is used in place of a PD controller, with the + term supplied by the EKF estimator, which at this stage of the study, estimated the unknown load. Fig. 5 shows the output with the PD+ controller.

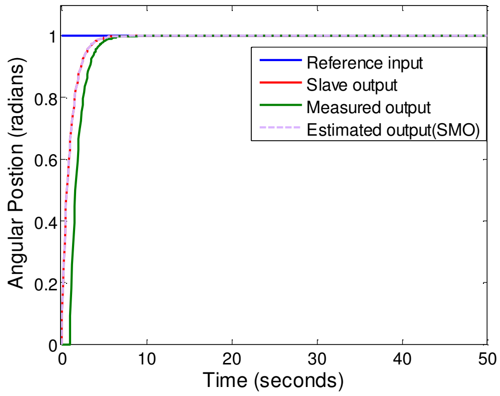


Fig. 5: Position output of system under a constant load and constant measurement delay (1 sec), with PD+ controller and EKF.

The improvement in the output performance with the combination of EKF and PD+ can be depicted in Fig.6, in which the measured and estimated outputs track the slave output very accurately in spite of the random measurement delay and unknown load, which also demonstrates an acceptable performance.

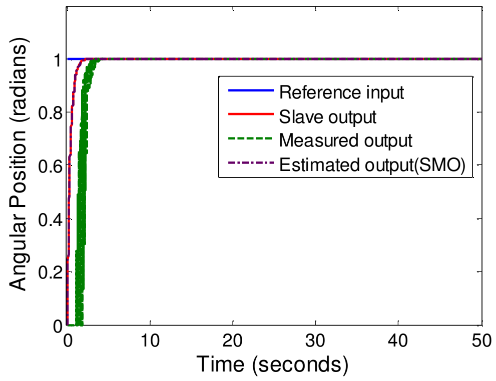
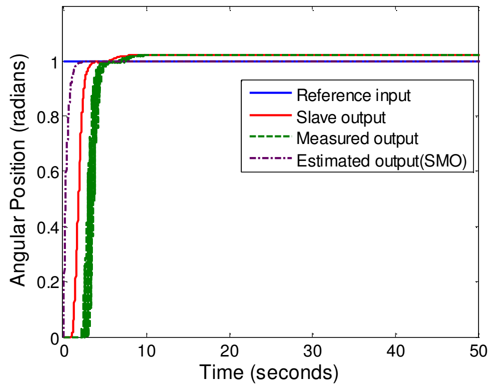


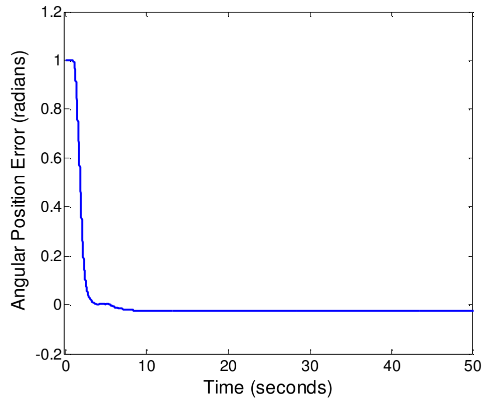
Fig. 6: Position output of system under constant load and random measurement delay (1-2 sec) with PD+ controller, SMO and EKF observer.

The performance of the SM observer was also tested for control delay. The response when both measurement and control delays are random, which is the case for internet based systems, is given by Fig. 7. Fig. 7(a), (b) and (c) show the slave position, error between the desired and actual slave output, and error between the actual slave output and estimated output, respectively. Fig 7(d) and (e) are the outputs from the EKF observer. As can be observed from the plots, the EKF observer provides an accurate estimation of the unknown slave load. The load is applied at t=5 seconds.

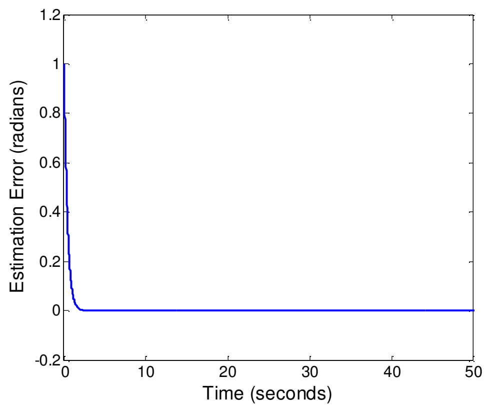
The computer simulations reveal an acceptable system performance even under *random* measurement and *random* control delay with the combined use of the SMO and EKF estimators; however the overlap and transparency between the actual and estimated slave positions is lost.



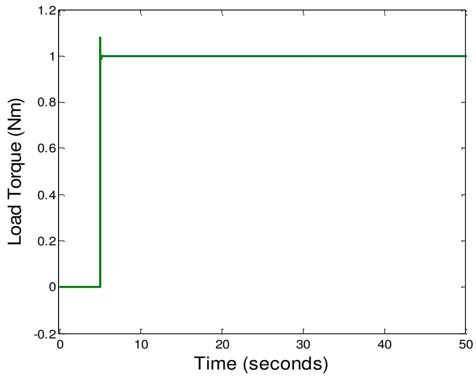
a) Position Output



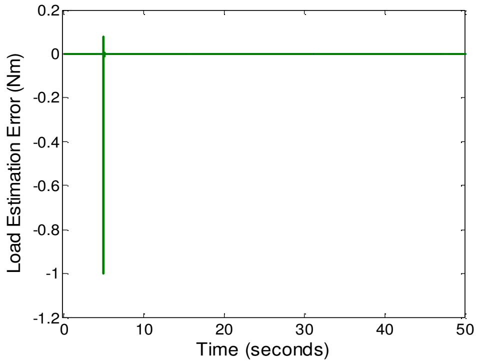
b) Position Error



c) Estimation Error



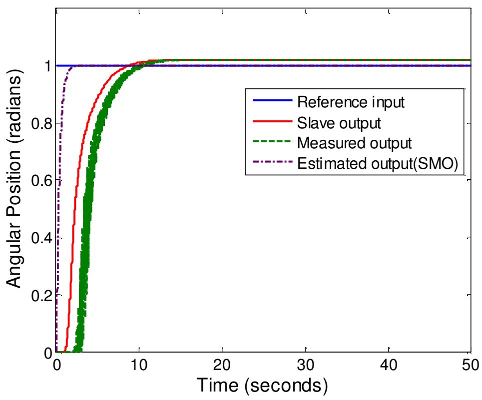
d) Estimated Load



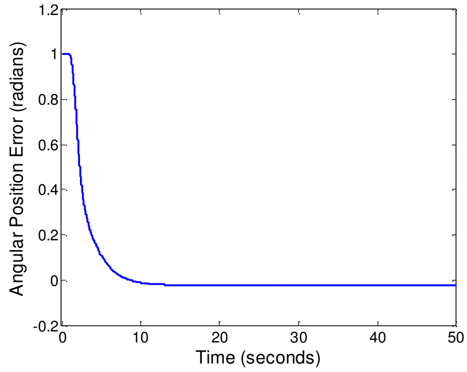
e) Load Estimation Error

Fig. 7: a) Position output, b) Angular position error, c) Estimation error, d) Estimated load torque (EKF), and e) Load estimation error of system under constant load, and simultaneously applied *random* control delay and *random* measurement delay (1-2 sec) with PD+ controller, SMO and EKF observer.

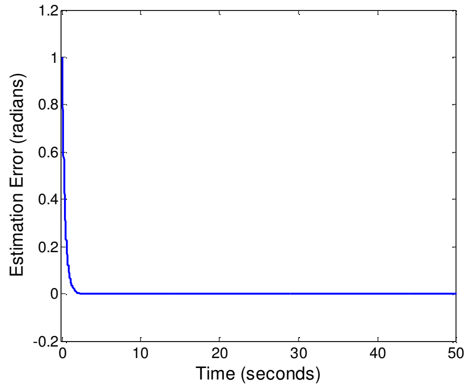
As this study depends on simulations, it has been easy to make the estimator model and the actual model identical, but in practice, this is not expected to be easily achieved or achieved at all. For example, inertia (J) and viscous friction (B) of the controlled system (slave in this case), may not be known accurately, or may vary with environmental and load conditions. Hence the system is tested for its robustness for parameter changes and the results are shown in Fig. 8 and 9.



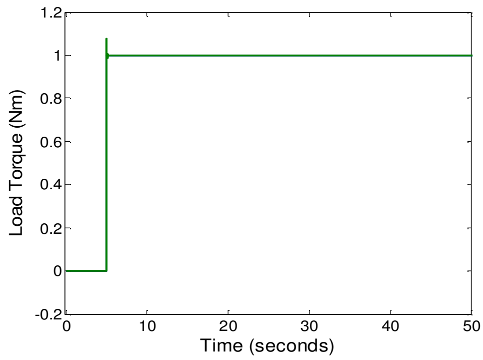
a) Position output.



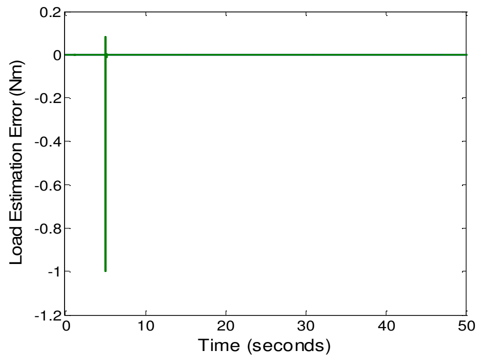
b) Position Error



c) Estimation Error



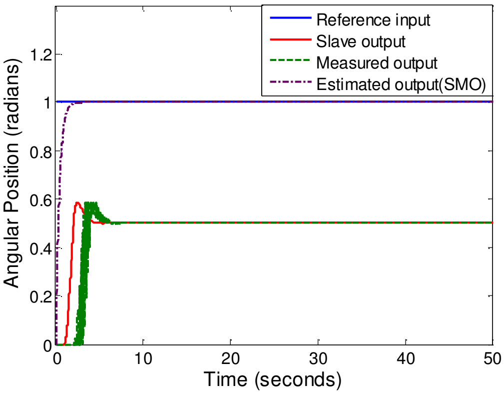
d) Estimated Load



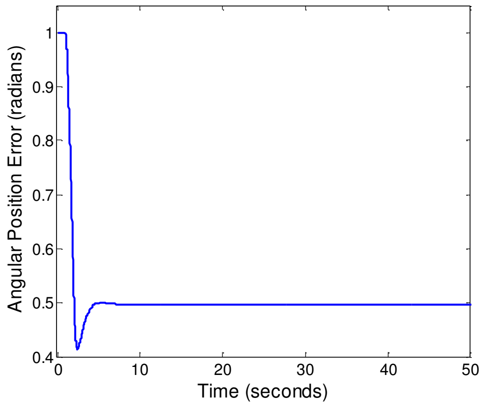
e) Load Estimation Error

Fig. 8: a) Position output, b) Angular position error, c) Estimation error, d) Estimated load torque (EKF), and e) Load estimation error of system under constant load, random control delay and measurement delay (1-2 sec) with inertial variation(J = 2*J) with PD+ controller, SMO and EKF observer.

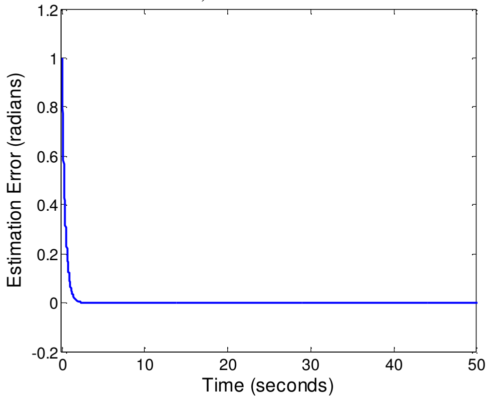
From fig. 8(a), it can be noted that the system transparency and the overlap of the estimated and actual slave position is lost once again, as the J variations have not been considered in the EKF at this stage of the study.



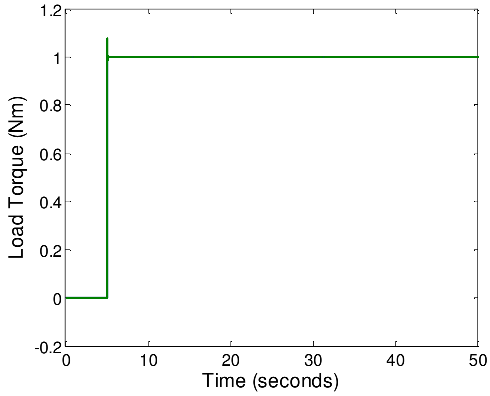
a) Position Output



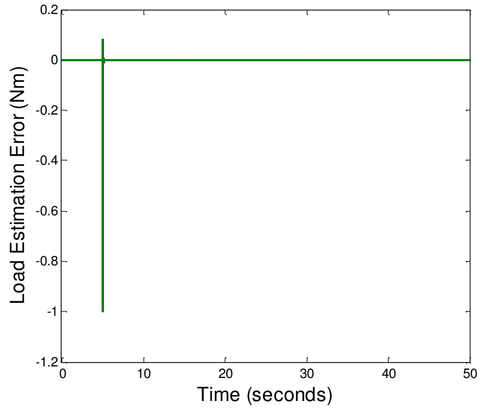
b) Position Error



c) Estimation Error



d) Estimated Load



e) Load Estimation Error

Fig. 9: a) Position output, b) Angular position error, c) Estimation error, d) Estimated load torque (EKF), and e) Load estimation error of system under constant load, random control delay and measurement delay (1-2 sec) with and doubled viscous friction (B) with PD+ controller, SMO and EKF observer.

The performance of the system is affected negatively also by viscous friction (B) variations as expected and shown in Fig. 9.

IV. CONCLUSION

In this study, a SM based novel observer and an EKF based disturbance observer were developed and tested with computer simulations specifically for the compensation of measurement delay for internet based bilateral control or teleoperation systems. The system was tested for a master-slave system, where the slave was a 1 DOF robotic arm. A PD+ controller was designed for the control of the arm. Simulations were conducted to test the system performance for different settings. The results demonstrated the successful performance of the developed observers against constant and random measurement delays and unknown load variations on the slave side. The simulations also demonstrated acceptable performance under simultaneously applied random measurement and control delay (with no direct measures taken for control delay). This may be interpreted as the result of these delay effects being estimated by EKF inside the constant disturbance term, hence demonstrating an advantage of the proposed SMO and EKF combination over previous studies in bilateral control systems.

The system was also tested for parameter changes (*J*, *B*). The performance deterioration caused by these variations indicate the need for inertia and friction estimation on the slave side, which will also be included in the EKF observer. This aspect and improvement of the SMO observer for practical implementation will be subject to our next study.

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