Control and Measurement Delay Compensation in Bilateral Position Control

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Abstract— **The main aim of this study is the improvement of the previously presented disturbance observer based bilateral control approaches of the authors with a delay regulator and a model tracking control (MTC) that runs on the slave side. These improvements eliminate the problems related to variable time delay inherent to such systems and model mismatch, respectively, and, hence, addressing the control and measurement delay problems in bilateral control applications. The performance is evaluated experimentally on a single-link arm controlled over the internet. The results demonstrate a significant improvement over the previously presented results obtained under load uncertainties and randomly varying network delays both in the control and feedback loop.**

Keywords— **Bilateral Control, Communication Delay, Disturbance Observer, Model Tracking, Model Tracking Control**

I. INTRODUCTION

A recent approach in bilateral control is the consideration of the communication delay effect as a disturbance, which is then addressed by the design of an observer [1]-[4], namely, a communication disturbance observer (CDOB), also discussed in [5], [6], [7], and [8]. The method is shown to be more effective than the Smith-predictor approach due to its independence of modeling errors and capability to handle variable delays as normally expected with the Internet. Moreover, this method can be applied to both SISO and MIMO systems [9], [10]. The CDOB approach presented in these papers lumps the delays in the control and measurement loop and proposes a 1st-order observer derived under the assumption of a linear system. As a result, the stability and performance of the system under load is totally dependent on the cutoff frequency, g, of the low or band pass filter of the CDOB [11], which dictates the behavior of the system. Although performing well under constant delay, the authors mention ongoing problems in practical applications under variable time delay. Also, no analysis is provided under different load effects. Additionally, the authors interpret the offset in the steady state (even under the no delay condition) to be caused by the unknown slave parameters, which, when combined with other system nonlinearities and actual delays of the internet, call for additional solutions to the problem of bilateral control.

This study builds on another disturbance observer approach taken for the solution of network delays in bilateral control [12], [13], [14]. The main structure of this approach is based on a sliding mode based communication disturbance observer (SMO) running on the master side and estimating the actual slave position and velocity *under measurement delay only*; an EKF based load estimator to estimate the unknown load (and potentially unknown parameters) of the slave, and a PD+controller that controls the system dynamics and compensates the estimated disturbance on the slave side. One negative aspect of this topology is that the SMO based communication disturbance observer is effected negatively from the variable pocket delay in communication, as well as the model mismatch. Another problem is the parameter and model dependency of the EKF, which becomes indicative in the obtained results under inertia, friction, and load changes. Moreover the disturbance suppressor has a dynamic, and this dynamic can cause small errors in acceleration. Unfortunately, in position control, these errors grow rapidly because of double integrator nature of the plant. Consequently, the experimental results of the previous studies demonstrate some transient and steady state errors even with constant network delay, which remain stable, but grow significantly under random measurement and control input delay. However, the latter is expected, as the SMO is designed specifically for the delayed feedback measurements. It should also be noted that these errors also have a compounding effect on the overall system performance.

This study aims to address these problems via the improvement of the communication problems as well as the model/parameter mismatch problem of the estimator on the slave side. To reduce communication problems, the delay regulator proposed in [15] is used, which reduces communication pocket loss and pocket disarrangement problems dramatically. This regulator works fine but its performance is limited with the length of the buffer in use. This approach, which was initially tested for our previous network delay compensation scheme in [14] under variable network delay, resulted in significantly reduced steady state and drift errors. These results, which are now comparable to those obtained for constant network delay, will not be presented here due space limitation, but instead, will be discussed in relation to the developed new scheme. As for the aim of overcoming the model mismatch problem in our previous studies with the EKF based load estimator, the slave side is also supported with a model of the slave now (similar to the master side), which provides the feedback to the master side. The SMO based disturbance observer only handles the communication delay, which is now reduced to a constant delay by a delay regulator, but still exists due to buffer length limitations. Obtaining the feedback from the slave model also provides us with the opportunity to design the master and slave control systems separately. The connection between the actual plant and its dynamic model is supplied by the model tracking control (MTC). This configuration does not give rise to the previously encountered position error problem, which gets compounded by double-integrator effects; in this new configuration, the position information is generated by the model, and further corrected by the model tracking controller. However, it is still required that both master and slave start with the same initial conditions.

The proposed observer-regulator-controller group is tested for step and bi-directional load and reference trajectories under random measurement as well as random control input delays. Throughout the experiments, the emulated random delay varies between 100-350 milliseconds which is the measured time delay from France to USA using UDP/IP internet protocol[16].

II. PROPOSED REGULATION SCHEME FOR VARYING TIME DELAY

While the purpose is bilateral control using Internet as an communication medium, it is necessary to define delay characteristic of Internet Protocols. Currently more general used IP(Internet Protocols) are the Transport Control Protocol (TCP/IP) and the User Datagram Protocol (UDP). TCP provides a point-to-point channel for applications that require reliable communication. It is a higher-level protocol that manages to robustly string together data pockets, sorting them and retransmitting them as necessary to reliably retransmit data. Further, TCP/IP is confirmation based, meaning it transmits data and waits for confirmation from the other side. If not, it retransmits. With TCP/IP there is no data loss. Figure 1 top shows cross Atlantic round latency time delay between Georgia Tech, Atlanta, and Metz France, and bottom shows a sine wave sampled at 10 milliseconds travel same way, both are sent by TCP/IP. The experiment was carried out on a typical work day during mid after noon. It is easily seen that the delay varies substantially, ranging from 100 milliseconds to 3000 milliseconds. It is also noted in the figure below that although no information is lost in the TCP/IP based communication, it is evident from the figure that data sampled at different points in time gets lumped together along the way and arrives simultaneously at the destination. So the shape of the sine wave is disturbed. These reasons make TCP/IP based communication unfavorable for real-time control. [9]

The UDP protocol doesn't guaranteed communication between two applications on the network. While TCP/IP is connection based, UDP is just a simple serial communication channel. Much like sending a letter through mail, UDP doesn't confirm arrival. So retransmitting data is eliminated, which can cost data loss. Figure 2 top shows cross Atlantic round latency time delay between Georgia Tech, Atlanta, and Metz France, and bottom shows a sine wave sampled at 10 milliseconds travel same way, both are sent by UDP/IP. The experiment was carried out on a typical work day during mid after noon. It is easily seen that the delay varies substantially, ranging 100 milliseconds to 250 milliseconds. It is seen that in UDP/IP shape of sine wave is more similar to original one. A few datagrams are also arrived simultaneously and some 12 to 16 percent of information is lost along the way. For those reasons, most commonly chosen protocol for real-time control is UDP. [16]

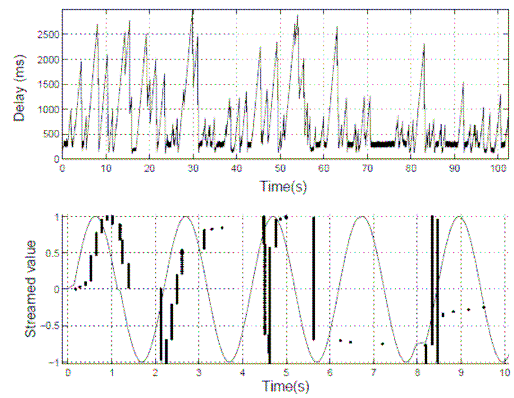

Fig 1. Top: Cross Atlantic round trip time delay between Georgia Tech, Atlanta and Metz, France using TCP [16]

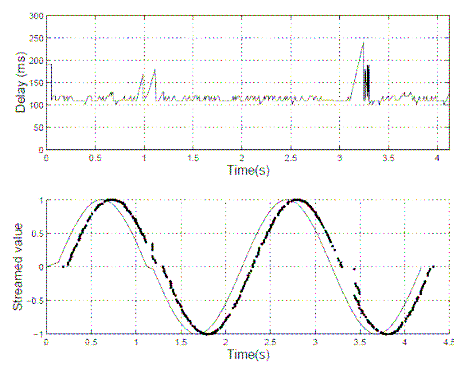

Fig 2. Top: Cross Atlantic round trip time delay between Georgia Tech, Atlanta and Metz, France using UDP [16]

In the proposed delay given for the regulator in Figure 3 based on [15], the UDP pocket is extended by the previous 31 sample values and a Sequence ID whose maximum value is the buffer length, L. The transmitted UDP pocket is written to the memory's Sequence IDth cell to guarantee that the output is sequential. Because of message loss there can be null cells. However if there is any valid cell in the 31 cells, which are filled with extended 31 values in UDP pocket, the valid one is used. Hence, the data loss problem is also reduced, since as a result of this regulator, the data does not come from internet at constant sample rate, but it is obtained from the buffer in

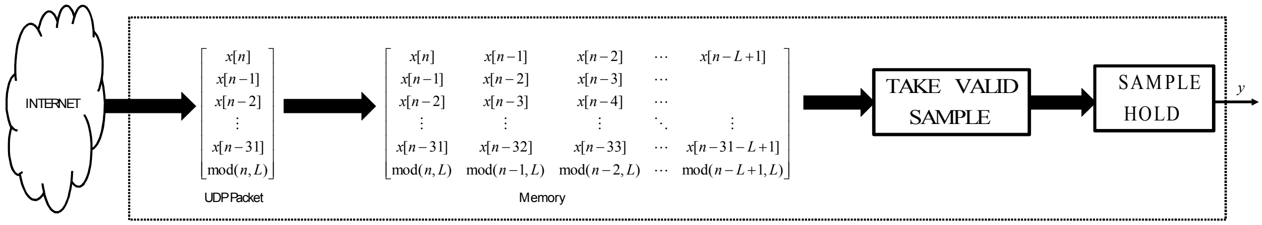

Fig 3. Information Flow in Time Delay Regulator

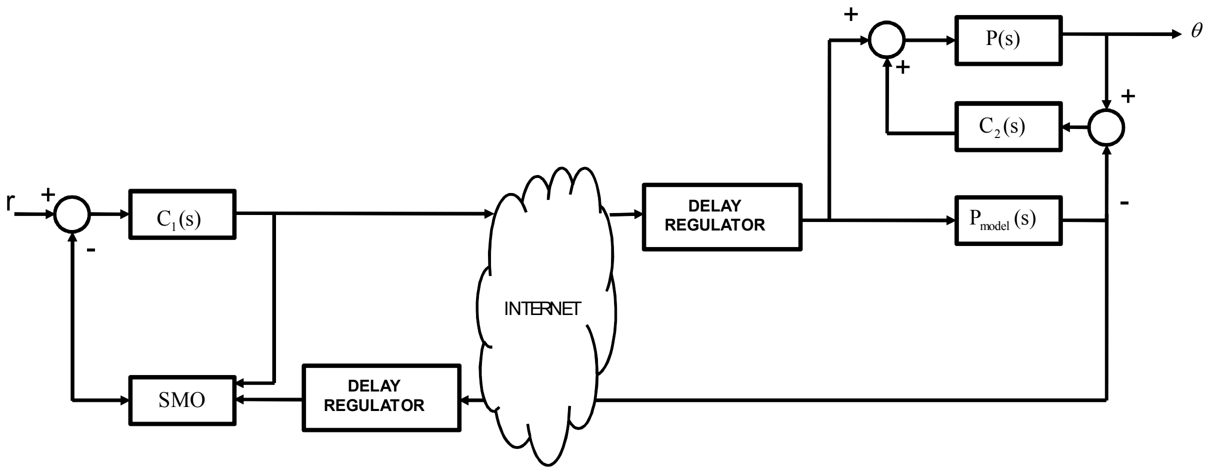

Fig 4. Proposed Architecture

constant time sample. Therefore the delay is regulated to a constant value.

III. PROPOSED CONTROL SCHEME UNDER FIXED TIME DELAY

In the proposed configuration given with the topology in Figure 4, there is an acceleration based SMO observer proposed in [12-13] at the master side. At both master and slave sides delay regulators are work to stabilize delay to a constant value. And at the slave side there is a model tracing control structure. Controller C2 is force system to follow model. And the feedback from the Internet is coming not from real process, from model process. So disturbances are suppress with model predictive control. Although we use delay Regulator there can be still some problems because of Internet. SMO's main duty is reduced these effects.

I.1. Design of SM Observer

The SM observer aims to estimate the actual slave position and velocity in spite of the delay in the feedback loop. The observer takes the following model into consideration:

$$\theta_1(t) = \omega_1(t) \tag{1}$$

$$\dot{\omega}_1(t) = \frac{K_{tn}}{J_n} u(t) - \frac{B_n}{J_n} \omega_e(t) + u_0(t) \tag{2}$$

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), $u_o(t)$ is control input of the observer (to be determined based on SM theory)
The estimated states could be represented as

$$\begin{aligned} \dot{\theta}_e(t) &= \omega_e(t) \\ \dot{\omega}_e(t) &= \dot{\omega}_m(t) - \left[u_o(t)\right]_{eq} \end{aligned} \tag{3}$$

where $[u_o(t)]_{eq}$ is the equivalent control.

The applied observer control $u_o(t)$ is designed based on the SMC framework, with an aim to satisfy the Lyapunov stability conditions for the sliding mode manifold $\sigma(t) = C e_{\theta 1}(t) + e_{\omega 1}(t)$ where $e_{\theta 1}(t)$, $e_{\omega 1}(t)$ are as follows:

$$e_{\theta 1}(t) = \theta_m(t) - \theta_1(t) \tag{4}$$

$$e_{\omega 1}(t) = \omega_m(t) - \omega_1(t) \tag{5}$$

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

The Lyapunov candidate is taken as follows with its derivative to satisfy the following conditions:

$$V(t)=\sigma^2(t); \quad \dot{V}(t)=\sigma(t)\dot{\sigma}(t)=-D\sigma^2(t) \qquad (6)$$

$$\dot{\sigma}(t)=Ce_{\omega 1}(t)+\dot{\omega}_m(t)-\dot{\omega}_1(t). \qquad (7)$$

(6) and (7) are used to derive the SM control law as follows[17]:

$$u_o(k)=u_o(k-1)+\left[\frac{(1+DT)\sigma(k)-\sigma(k-1)}{T}\right]. \qquad (8)$$

The control in (8) will enforce the sliding mode to the manifold, $\sigma(t)=0$. The equivalent control that drives $\dot{\sigma}(t)=0$ is determined as below:

$$[u_o(t)]_{eq}=Ce_{\omega 1}(t)+\dot{\omega}_m(t)-\dot{\omega}_1(t)$$
$$=Ce_{\omega 1}(t)+\dot{\omega}_m(t)-\frac{K_{tn}}{J_n}\hat{u}(t)+\frac{B_n}{J_n}\omega_e(t) \quad (9)$$

From(1), $\frac{K_t}{J}u(t)=\frac{B}{J}\omega(t)+\dot{\omega}(t)+\frac{T_L}{J}$,

$$\frac{K_{tn}}{J_n}\hat{u}(t)=\frac{B_n}{J_n}\omega(t)+\dot{\omega}(t)$$
$$+\frac{1}{J_n}\left[\tilde{B}\omega(t)+\tilde{J}\dot{\omega}(t)-\tilde{K}_t\tilde{u}-K_{tn}\tilde{u}+T_L\right]$$

(10a)

Where;

$u(t)=\hat{u}(t)+\tilde{u}(t)$

$\hat{u}(t)$: control input generated on master side,

$u(t)$: control input of the slave,

$\tilde{u}(t)$: error in the input caused by the network delay.

Denoting all parameter uncertainties due to delay and other uncertainties by "~" and rated parameter values by "*n*" and all lumped uncertainties as "η",

$J=J_n+\tilde{J}$

$B=B_n+\tilde{B}$

$K_t=K_{tn}+\tilde{K}_t$

T_L : lumped load, coulomb, viscous etc friction and other uncertainties on the slave side.

Using these definitions, (9) becomes,

$$[u_o(t)]_{eq}=Ce_{\omega 1}(t)+[\dot{\omega}_m(t)-\dot{\omega}(t)]+\frac{B_n}{J_n}[\omega_e(t)-\omega(t)]-\frac{\eta}{J_n} \qquad (10b)$$

From (3), $\left[u_o(t)\right]_{eq}=\dot{\omega}_m(t)-\dot{\omega}_e(t)$, therefore substituting in (10),

$$\left[\dot{\omega}_e(t)-\dot{\omega}(t)\right]+\frac{B_n}{J_n}\left[\omega_e(t)-\omega(t)\right]=-Ce_{\omega 1}(t)+\frac{\eta}{J_n} \quad (11)$$

Inspecting (7), it can be said that $\sigma(t)\to 0 \Rightarrow$ indicates that $e_{\omega 1}(t)\to 0, \quad Ce_{\omega 1}(t)\to 0$; however, the fulfillment of this condition depends on η being zero, which requires the control input delay to be zero and the load effects(load and friction together) and slave parameters be known (or, estimated) as indicated in the η definition of (10a).

Only then, the system response will result in the estimated and actual slave velocity to converge; that is,

$$\omega_e(t)=\omega(t) \qquad (12)$$

However, the fulfilment of (12) does not guarantee the convergence of the position error to zero, unless all initial conditions are zero, or known. In order to ensure position convergence, the error dynamics in (11) should have a term depending on $\theta_e(t)-\theta(t)$.

I.2. Design of Slave Controller

The structure of the slave control system, which is based on a model tracking scheme, is represented in Figure 5. It should be noted that the global feedback of the integrated system is the output of the model system, $P_{model}(s)$. With this approach, the master and slave controllers can de designed separately.

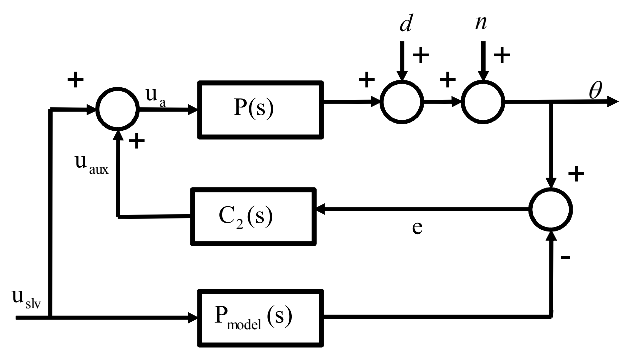

Fig. 5. Architecture of Model Tracking Control at Slave

The feedback used in the slave system is $e(s)$ and the reference model of the $P_{model}(s)$ is an explicit part of the control system. With this approach, it can be easily seen that both disturbance rejection and model following can be achieved simultaneously.

Here, the controller, $C_2(s)$ is configured as a compensator and its output $u_{aux}(s)$ is added on to the , $u_{slv}(s)$ which is the constant time delayed version of the control signal generated on the master side.

The compensator, $C_2(s)$ is designed such that the norm of the transfer matrix from $u_{slv}(j\omega)$ to $e(j\omega)$ be below some prescribed value in a given frequency range. This is the condition of model following. Moreover, the effect of disturbance $d(j\omega)$ and measurement noise $n(j\omega)$ on to the output $\theta(j\omega)$ are also maintained under a predefined value to fulfil the disturbance and measurement error rejection conditions, respectively [18].

On to these constraints, we also add the effect of the modelling error, which is considered with a multiplicative representation. We assume that an upper bound is given for the spectral norm of the multiplicative error matrix in the form of a scalar function, $e_M(\omega)$ [19].

The system proposed in Figure 5 can be expressed by the following equations:

$$\begin{aligned}\theta(s) = S(s)d(s) \\ + S(s)P(s)(I + C_2(s)P_{model}(s))u_{slv}(s) \\ - S(s)P(s)C_2(s)P_{model}(s)n(s)\end{aligned} \quad (13)$$

$$\begin{aligned}e(s) = S(s)d(s) \\ + S(s)(P(s) - P_{model}(s))u_{slv}(s) \\ - S(s)n(s)\end{aligned} \quad (14)$$

$$\begin{aligned}u_{aux}(s) = -(I + C_2(s)P(s))^{-1}C_2(s)d(s) \\ + (I + C_2(s)P(s))^{-1}(I + C_2(s)P_{model}(s))u_{slv}(s) \\ - (I + C_2(s)P(s))C_2(s)n(s)\end{aligned} \quad (15)$$

Where, $S(s) = (I + P(s)C_2(s))^{-1}$ is the sensitivity matrix

Firstly we should mention that, $P_{model}(s)$ should be stable. Then, it is clear that system stability is determined just by the closed-loop containing $P(s)$ and $C_2(s)$.

The performance parameters for model following are $\omega_r > 0$ and $\alpha_r > 0$ with typically $\alpha_r << 1$, which expresses the desired accuracy of the model following in a given set of frequencies, Ω_r ,where $\Omega_r = \{\omega \in R : \omega < \omega_r\}$. Then the condition can be defined as

$$\frac{\|e(j\omega)\|}{\|u_{slv}(j\omega)\|} < \alpha_r \quad \omega \in \Omega_r \quad (16)$$

Moreover for simplicity we assume that $d(s) = 0$ and $n(s) = 0$. To accomplish model following, we get the following sufficient condition from the equation for $e(s)$:

$$\sigma_{\max}[S(j\omega)] \le \frac{\alpha_r}{\sigma_{\max}[P(j\omega) - P_{model}(j\omega)]} \quad (\omega \in \Omega_r) \quad (17)$$

It is easily seen that the sensitivity decreases with increasing model mismatch, and decreasing α_r. Depending on the specific problem at hand, this condition may be not so restrictive and the sensitivity may be not necessarily low [18].

When the right-hand side of (17) is much smaller than 1, this condition can be rewritten approximately as

$$\sigma_{\max}[P(j\omega)C_2(j\omega)] \ge \frac{\sigma_{\max}[P(j\omega) - P_{model}(j\omega)]}{\alpha_r} \quad (\omega \in \Omega_r) \quad (18)$$

This condition also says that the loop gain should increase with both the mismatch between $P(s)$ and $P_{model}(s)$ and the inverse of α_r.

Performance parameters for disturbance rejection are $\alpha_d > 0$ which is typically $\alpha_d << 1$ and $\omega_d > 0$. Suppose that $\Omega_d = \{\omega \in R : \omega < \omega_d\}$ is a given frequency set where the disturbance $d(s)$ has the predominant energy. For simplicity, we also assume that $u_{slv}(s) = 0$ and $n(s) = 0$. Then, the disturbance rejection condition can be defined as

$$\frac{\|e(j\omega)\|}{\|d(j\omega)\|} \le \alpha_d \quad (\omega \in \Omega_d) \quad (19)$$

From the equation of $e(s)$, this condition gets the following form:

$$\sigma_{\max}[S(j\omega)] \le \alpha_d \quad (\omega \in \Omega_d) \quad (20)$$

which can also expressed in the following approximate condition [20]:

$$\sigma_{\min}[P(j\omega)C_2(j\omega)] \ge \frac{1}{\alpha_d} \quad (\omega \in \Omega_d) \quad (21)$$

when $\alpha_d << 1$.

Measurement error rejection performance parameters are $\alpha_n > 0$ which is typically $\alpha_n << 1$ and $\omega_n > 0$. Suppose that $\Omega_n = \{\omega \in R : \omega < \omega_n\}$ is a given frequency set where the measurement error predominantly has its energy. For simplicity, we will also assume that $r(s) = 0$ and $d(s) = 0$. Then the measurement error rejection condition can be defined as

$$\frac{\|\theta(j\omega)\|}{\|n(j\omega)\|} \le \alpha_n \quad (\omega \in \Omega_n) \tag{22}$$

From equation of $\theta(s)$ we can get the condition as the following form

$$\sigma_{\max}[T(j\omega)] \le \alpha_n \quad (\omega \in \Omega_n) \tag{23}$$

Where

$$T(s) = (I + P(s)C_2(s))^{-1} P(s)C_2(s) \tag{24}$$

Alternatively, from the equation of $\theta(s)$, the following form [20] can be obtained:

$$\sigma_{\max}[P(j\omega)C_2(j\omega)] \le \alpha_n \quad (\omega \in \Omega_n) \tag{25}$$

When $\alpha_n << 1$

The performance parameters for model uncertainty are $e_M(\omega) < 1$ for $\omega \in \Omega_r \cup \Omega_d$. For the adopted multiplicative model error, the stability robustness condition can be given by [19]:

$$\sigma_{\max}[T(j\omega)] \le e_M(\omega) \quad (\forall \omega) \tag{26}$$

Using (17) and (20) above expression can be modified [21]:

$$\sigma_{\max}[S(j\omega)] \le \frac{\alpha_r [1 - e_M(\omega)]}{\sigma_{\max}[P(j\omega) - P_{model}(j\omega)]}, (\omega \in \Omega_r) \tag{27}$$

And

$$\sigma_{\max}[S(j\omega)] \le \alpha_d [1 - e_M(\omega)] \quad (\omega \in \Omega_d) \tag{28}$$

If $\alpha_n << 1$, condition (23) can be rewritten like the following [15]:

$$\sigma_{\max}[T(j\omega)] \le \frac{\alpha_n}{1 + e_M(\omega)} \quad (w \in \Omega_n) \tag{29}$$

It is easily seen that the effect of model uncertainty is to make the constraints on S and T more restrictive.

From the equation of $\theta(s)$, we can see that $S(s)P(s)(I + C_2(s)P_{model}(s))$ behaves as a low pass filter because $P(s)$, $P_{model}(s)$ and $C_2(s)$ each exhibit low gains at high frequencies. Hence, the overall transfer matrix is approximately equal to $P(s)$. In view of this the value of ω_r is related to both $P(s)$ and $P_{model}(s)$. This means that the model following condition (15) does not necessarily imply model matching. This is the reason why we prefer to call the proposed procedure model tracking. Simulations carried out by now in the literature indicate it is reasonable to expect nice matching up to one decade above the reference model bandwidth [18]. Conditions presented through (14) to (17) constitute the key conditions for the design of robust compensators in order to achieve model tracking.

IV. EXPERIMENT RESULTS

In this section, the performance of the new approach that combines the delay regulator, SMO and MTC is tested for a master-slave system with a single-link arm under gravity effect as the slave. The experimental results are obtained under random measurement and input delays and load uncertainties on the slave side. For increased challenge, bi-directional reference and bi-directional load variations are applied to the system. A direct-drive motor driven single-link arm is used in the experiments, the parameters of which are listed in Table 1. The random delay is generated as a random signal varying between 100-350 milliseconds.

The experiment results are depicted in Figure 6 and 7, with Figure 6a and 7a demonstrating the angular positions. The blue lines are actual angular position read from the slave, black lines are angular position after internet communication delay, which we call delayed angular position, and red lines are after time delay regulation block, which we call delay regulated angular position, and green lines are output of SM based observer outputs. Figure 6b and 7b depict the results of angular where blue lines are angular velocity read from slave, which we call actual angular velocity, black lines are angular velocity after internet communication delay, which we call delayed angular velocity, and red lines are after time delay regulation block, which we called delay regulated angular velocity. Figure 6c and 7c depict the control input generated by the master. Blue lines shows signal before Internet delay, black lines are after Internet delay and red lines are after time regulation. Figure 6d and 7d show applied auxiliary control signal generated from Model tracking control, and finally Figure 6e and 7e show applied disturbance signal in terms of control signal.

From the figures, it can be seen that the tracking accuracy is very high in the no-disturbance case. On the other hand, there is some overshoot under sine type disturbances case, however, the stability is maintained, and the steady state errors are acceptable. It should be also noted that in this study, to pose significant challenges for the proposed scheme, very high load uncertainties are imposed on the system, which makes the resulting performance acceptable.

TABLE I
EXPERIMENT PARAMETERS

Parameter Name	Parameter Value	Description
V_{qn}	60 V	Motor nominal voltage
i_{qn}	5 A	Motor nominal current
R_q	0.6 Ω	Motor phase windings resistance
L_q	0.005 H	Motor phase windings inductance
K_b	2.3 V sec/rad	Back e.m.f constant
T_{en}	10 Nm	Motor nominal torque
K_{vi}	1 A/V	Motor driver gain
ω_n	4π rad/sec	Motor nominal speed
T_{em}	15 Nm	Motor maximum torque
K_t	2 N-m/A	Torque constant
J	0.012 kg-m^2	Effective Inertia
B	0.207 N-ms/rad	Effective Viscous friction
T_L	10 sinθ N-m	Load torque

V. CONCLUSIONS

The major contribution of this study is improving the previously presented disturbance observer based bilateral control approaches with a delay regulator and model tracking control, eliminating the problems related to model mismatch and variable time delay inherent to such systems, hence opening the path for more realistic bilateral control applications.

The experimental results demonstrate that in all conditions, the slave system tracks the control input generated by the master under high disturbance and model uncertainty effects. Problems related to varying time delay is suppressed by the network delay regulator. Moreover, the steady state errors and slight drift noted in our prior studies (due to inaccurate knowledge of slave parameters) are suppressed by the proposed Model Tracking Control.

VI. ACKNOWLEDGMENT

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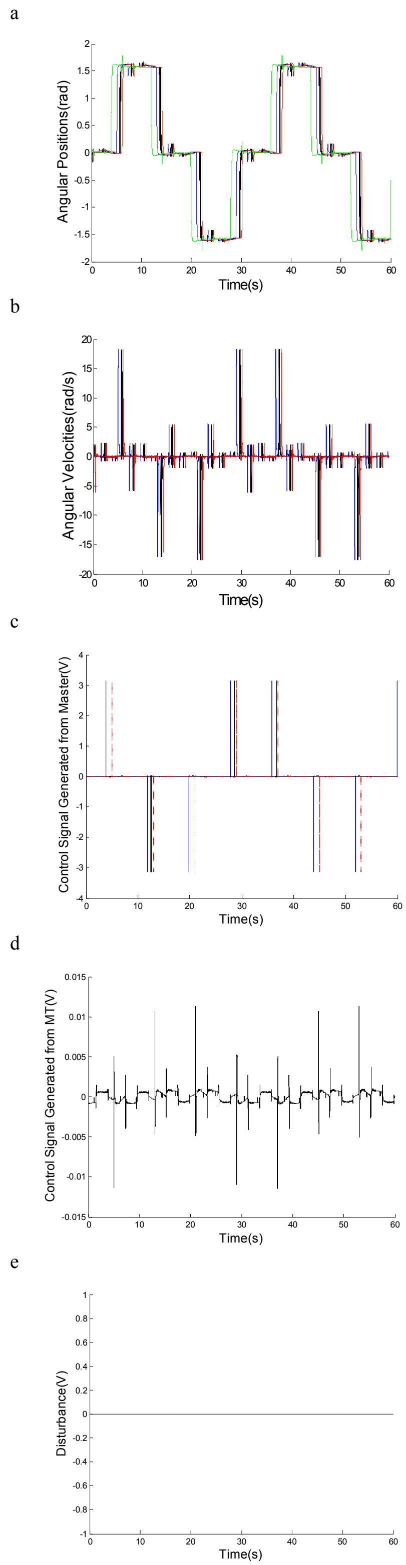

Fig 6. Experimental results without disturbance
a-)Angular positions b-)Angular velocities
c-)Control signal generated from Master
d-)Control Signal Generated by Model Tracking
e-)Applied Disturbance

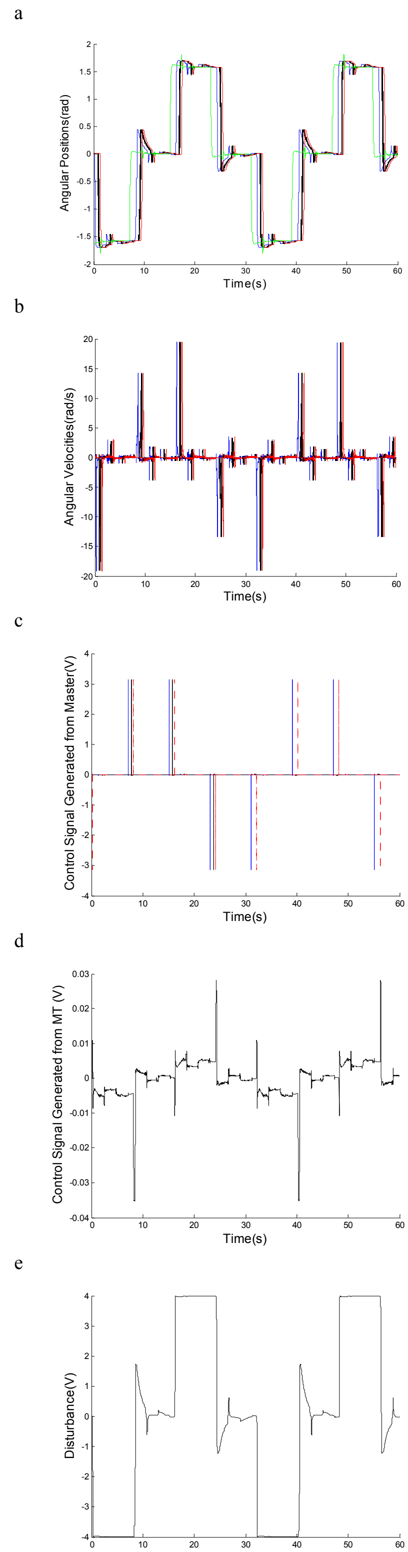

Fig 7. Experimental results with sinus disturbance
a-)Angular positions b-)Angular velocities
c-)Control signal generated from Master
d-)Control Signal Generated by Model Tracking
e-)Applied Disturbance