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Predictive Input Delay Compensation for Motion Control Systems

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***Abstract*—This paper presents an analytical approach for the prediction of future motion to be used in input delay compensation of time-delayed motion control systems. The method makes use of the current and previous input values given to a nominally behaving system in order to realize the prediction of the future motion of that system. The generation of the future input is made through an integration which is realized in discrete time setting. Once the future input signal is created, it is used as the reference input of the remote system to enforce an input time delayed system, conduct a delay-free motion. Following the theoretical formulation, the proposed method is tested in experiments and the validity of the approach is verified.**

I. Introduction

Along with the growth of internet communication, the attention on applications of motion control over network became more and more popular. Among such applications, an intense focus has been put on the teleoperation systems, in particular bilateral control systems that can work over the two ends of a network [1]. A major problem of teleoperation systems is the existence of time delay throughout the control and measurement channels which has the potential to destabilize an otherwise stable closed loop system.

Several studies have been proven to perform successfully for teleoperation with time-delays. Among them, methods based on passivity [2], [9], [10] and methods based on wave variables and scattering theory [4]-[8] have frequently been adopted in different studies. Many researchers proved the stable operation of these methods in various settings. However, both of these methods still lack in terms of transparency, which is a must in teleoperation systems [3]. Quantitative and analytical comparisons of those methods can be found in [11] and [12]. For more detailed information, reader is referred to the historical survey given in [1].

Besides the solutions related to passive power transfer and scattering theory, methods based on Disturbance Observer have also been popularized in the recent years [13], [14], [15]. Based on the concept of network disturbance, these methods are shown to overcome the measurement delay in motion control systems [16], [18].

On the other hand, in all of the above mentioned methods although stabilization goal is achieved, full synchronization of the motion between the separated systems cannot be achieved due to the existing delay in the input channel. In the literature, several methods have been proposed to deal with input delay. In [19], a robust controller is proposed for input time delay based on a nonminimum phase disturbance observer. The proposed controller aimed to achieve stable tracking after the input delay. Many other studies have focused on the use of variable structure systems [21], [22], [23]. In [20], a sliding mode controller is proposed to achieve robust stabilization of uncertain input delay systems with nonlinear perturbations. The sliding surface is constructed based on a predictive state formulation which makes use of the past data of system states for a period equal to the magnitude of input time delay. Although this method performs relatively good in the presented simulations, it makes use of past data for the prediction of current motion and there is no discussion about the prediction of future motion. In a recent study, authors presented a structure for teleoperation systems based on Bayesian Predictions [24]. However, their scheme is based on the use of posterior probabilities from past data to enhance the current estimate of a system again without any discussion for the expected future motion of the system.

In this paper, we present an analytical approach to predict the future motion of a system with a novel predictor structure. The predictor is based on the use of convolution integral along with the past and present inputs for a system of known dynamics. Derivation of the predictor is made in a discrete time setting based on the assumption of nominal behavior for the remote system.

The organization of the paper is as follows. In section II, a brief background on the system definition is made and the concepts of disturbance observer (DOB) and Communication Disturbance Observer (CDOB) are introduced for nominal system behavior and stable tracking of given reference on the remote system respectively. In section III, derivation of the future data predictor is presented. In section IV, the realization of the predictor structure in a motion control system is formulated based on the assumption that the remote plant has nominal behavior. Section V presents the experimental results. Concluding remarks and possible future study are given in sections VI and VII respectively.

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II. Background

A. System Definition

In the following analysis, derivation of the predictor structure will be made on a single DOF motion control system for which the plant dynamics can be given as

$$a_n\ddot{q}(t) = \tau(t) - \tau_{dis}(t) \tag{1}$$

where, a_n, $\tau_{dis}(t)$ and $q(t)$ represent the nominal plant inertia, disturbance torque acting to the plant and the generalized coordinate of motion respectively. The input torque $\tau(t)$ can be modeled as a scaler multiple of the control (also referred as input) current $i_c(t)$ with the nominal torque constant K_n. This way the equation of motion for the plant can be recast as;

$$a_n\ddot{q}(t) = K_n i_c(t) - \tau_{dis}(t) \tag{2}$$

The term $\tau_{dis}(t)$ in equation (2) is assumed to cover all undesired effects including the viscous friction ($b(q,\dot{q})$), deviations from the nominal values for torque constant (ΔK_n) and inertia (Δa_n), gravitation ($g(q)$) and all other non-modeled external torques (τ_{ext}). Hence, the overall disturbance can be modeled as follows;

$$\tau_{dis} = \Delta a_n\ddot{q} + \Delta K_n i_c + b(q,\dot{q})\dot{q} + g(q) + \tau_{ext} \tag{3}$$

B. Disturbance Observer and Acceleration Control

In order to obtain robust tracking, disturbances over the system given in (2) should be removed. In order to cancel the disturbance acting on the system a disturbance observer (DOB) can be realized [25]. DOB can effectively increase the robustness of a system. However, due to the low pass filter used in DOB structure, the disturbance might not always be fully compensated. In particular for cases based on an observer structure over a time delayed loop, the controller is proven to be blind against the divergence of the remote plant from its corresponding reference [17]. Hence, a secondary controller should be added over the DOB structure to further push the remote plant into nominal behavior and to enforce tracking of the desired reference. For further details about the use of DOB in a time delayed control system, reader is referred to [16]. In this study, Disturbance Observer is used to make the slave system behave with nominal parameters and hence utilization of the prediction based controller derived in the following sections is carried out in acceleration domain.

C. Overview of Time Delayed Effect and CDOB

A motion control system with time delay is one in which real time signal transmission is hindered due to the network between the remote plant and the controller. The time delay can exist either in one of the channels (i.e. input channel or measurement channel) or (more generally) in both channels. The existing time delay in the signal transmission has different drawbacks for measurement and input channels. When there is time delay in the measurement channel, controller cannot obtain the information of remote plant states on time and cannot generate the necessary control input. This is a primary problem since with an uncompensated delay in the measurement channel, it is impossible to talk about the overall system stability. The solution for measurement delay can be obtained by estimating the future states of the remote plant via an observer structure. One such structure is Communication Disturbance Observer (CDOB) presented in [14]. In CDOB structure, the effect created by the measurement delay is considered as a disturbance in acceleration dimension which can be modeled as

$$\tau_{dis}^{nw}(t) = K_n i_c(t) - a_n\ddot{q}_s(t - D_m) \tag{4}$$

where $\tau_{dis}^{nw}(t)$ represents the network disturbance, D_m stands for the delay in the measurement channel and $q_s(t)$ represents the remote system (i.e. slave system) position. Under the assumption that the remote system has a nominal structure, the network disturbance can be estimated with a DOB which is termed as the Communication Disturbance Observer due to obvious reasons.

The estimated network disturbance stand for the torque that is supposed to act on the slave plant during measurement delay. Since the slave plant is enforced to behave nominal with DOB, the estimated network disturbance can be divided by the nominal inertia of slave plant and be integrated to give the velocity difference that is supposed to exist during the measurement delay time. Mathematically, we have;

$$\Delta\dot{q}_s(t) = \frac{1}{a_n}\int \tau_{dis}^{nw}(\varphi)d\varphi \tag{5}$$

Addition of this velocity difference to the delayed slave velocity gives the estimated velocity of the slave plant as shown below

$$\hat{\dot{q}}_s(t) = \dot{q}_s(t - D_m) + \Delta\dot{q}_s(t) \tag{6}$$

The depiction of CDOB structure is given in Fig. 1 below. Further information about CDOB can be found in [13] and [14], whereas a stability analysis is given in [16].

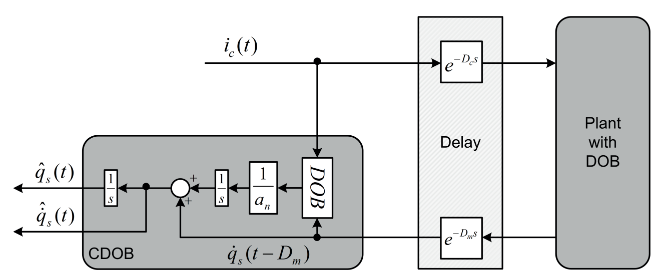

Fig. 1. Structure of CDOB

The system compensated with the CDOB structure exhibits stable behavior with the estimation of the real time slave motion measurement. In other words, CDOB converts the overall system to one without the measurement delay. Using the estimation from CDOB, master side controller can generate the necessary input reference that is supposed to act on the slave system after the input channel delay. However, due to the input channel of the network, slave system can track the motion of master system only after an input delay.

In order to have full synchronization of motion between master and slave plants, the effect of input delay should also be eliminated from the overall control loop. Conventionally, the motion of master is imposed by an operator and it has an arbitrary structure. Hence, it is impossible to construct a causal estimator since the future input of the master operator is unknown. So, a predictor for compensation of the input delay can only be based on a (noncausal) structure that can anticipate the behavior of master system. In the following section, one such predictive structure is derived to estimate the future motion of master system under a few practical restrictions and assumptions.

III. Derivation of Predictor

In most physical systems, the nature of the source of force does not imply continuity. However, in practice, the force exerted on the manipulator by the human operator is transmitted through a series of intermediate elements (i.e. hands, fingers, skin and muscles in general) all of which exhibit a continuum of connected mass-spring-damper like structures. Having considered the transmission path through several second order systems, it is usually a valid assumption to take the structure of input force for the manipulator as being continuously differentiable. In light of this assumption we can continue our analysis.

Let $u(t)$ be a continuously differentiable input function of time. In order to anticipate the future behavior of such a function, the well known Taylor Approximation can be used. So, the following Taylor series expansion can be utilized for the incremental anticipation of $u(t)$;

$$u(t+\delta t) = u(t)+\frac{u^{(1)}(t)}{1!}(\delta t)+\frac{u^{(2)}(t)}{2!}(\delta t)^2+\frac{u^{(3)}(t)}{3!}(\delta t)^3+\ldots \tag{7}$$

where, $u^{(n)}(t)$ represents the n^{th} derivative of function $u(t)$ and δt stands for an incremental time period. In equation (7), without loss of generality, one can drop the higher order terms (HOT) in the Taylor Series, truncating the expansion after the first order derivative. The error made in disregarding the HOT is directly correlated to the magnitude δt. Having a small enough δt, the approximation error becomes negligible and hence one can write;

$$u(t+\delta t) \approx u(t) + \frac{du(t)}{dt}(\delta t) \tag{8}$$

Practical realization of a system is always made in discrete-time. Hence, it is important to recast equation (8) in an equivalent representation for the next step anticipation of a discretized function $u[kT]$ which can be given as;

$$u[(k+1)T] \approx u[kT] + \frac{du[kT]}{dt}T \tag{9}$$

where kT is the k^{th} sample of the discrete system with a sampling time T. In (9), there are several ways to evaluate the derivative of the discrete time function. One way of evaluating the derivative is using the so called Backward Euler method. Writing the derivative explicitly with Backward Euler, one can rearrange (9) as follows;

$$u[(k+1)T] \approx u[kT] + \left(\frac{u[kT] - u[(k-1)T]}{T}\right)T \tag{10}$$

For simpler analysis, let us abbreviate one step further value of the input function (i.e. $u[(k+1)T]$) as u_1, the current value of function (i.e. $u[kT]$) as u_c and one step previous value of the function (i.e. $u[(k-1)T]$) as u_p. Now, rewriting equation (10), we can obtain the following identity to approximate the next step value of function u;

$$u_1 \approx 2u_c - u_p \tag{11}$$

Equation (11) is of crucial importance since it can give a prediction for the next step value of a function based only on the information of the current and one step previous data. Originating from this equation, one can propose an iteration for the further future steps of the function u based on the available data as follows;

$$\begin{aligned}
u_2 &\approx 2u_1 - u_c \\
u_2 &\approx 2(2u_c - u_p) - u_c \\
u_2 &\approx 3u_c - 2u_p \\
\\
u_3 &\approx 2u_2 - u_1 \\
u_3 &\approx 2(3u_c - 2u_p) - (2u_c - u_p) \\
u_3 &\approx 4u_c - 3u_p
\end{aligned} \tag{12}$$

Looking at the given iterations in equation (12), one can express the prediction for the N^{th} future step of the input function $u[kT]$ (abbreviated as u_N) in terms of its current and one step previous values as follows:

$$u_N \approx (N+1)u_c - Nu_p \tag{13}$$

The approximated prediction given in equation (13) has two major sources of error. One error is due to the assumption that the higher order terms in the Taylor Expansion is neglected and the second error is due to discretization. It is important to note here that both of these errors tend to zero as the incremental time step (δt for continuous and T for discrete representation) becomes smaller. In other words, we have;

$$\lim_{T\to 0} u_N = (N+1)u_c - Nu_p \tag{14}$$

So, having a very low sampling time, one can obtain an accurate estimation for the future behavior of the function $u(t)$ with the identity given in equation (14).

IV. System and the Predictor

A. System

In order to implement the predictor proposed in the previous section, it should be realized in a motion control system. The mathematical representation of a 1-DOF system with disturbance observer can be given as follows;

$$K_n i^{ref}(t) = a_n \ddot{q}(t) + \delta\tau_{dis} \tag{15}$$

where, $\delta\tau_{dis}$ represent the uncompensated disturbance over the system that can possibly exist due to the imperfections in DOB. With additional compensation, it is possible to have full disturbance rejection, making $\delta\tau_{dis}$ negligibly small [17]. Under the assumption that perfect disturbance cancelation exists (i.e. $\delta\tau_{dis} \approx 0$), the system can behave linear. Hence, one can recast the dynamics given in equation (15) in the following state space canonical representation;

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

where, the state vector x, state transition matrix A, input matrix B and the system input u can be given as follows:

$$x = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{K_n}{a_n} \end{bmatrix}, u = i^{ref}(t) \tag{16}$$

The output matrix C can be designed in correlation with the measurement obtained from the system.

Utilizing the convolution integral from linear system theory, it becomes possible to predict the future response of the system given in (16) using the following predictive integration:

$$x(t+\xi) = e^{A\xi}x(t) + \int_0^{\xi} e^{-A\theta}Bu(t+\theta)d\theta \tag{17}$$

where, the future values of the system input $u(t+\theta)$ is assumed to exist. Without loss of generality, equation (17) can be rewritten in the discrete time setting for implementation purposes as follows:

$$x[\alpha T] = e^{A\alpha T}x[0] + \sum_{m=1}^{\alpha} e^{-AmT}Bu[mT] \tag{18}$$

where, $x[0]$, $u[mT]$ and $x[\alpha T]$ represent the current value of the state vector, m step forward prediction of system input and α step forward prediction of the state vector respectively. For the system given in (16), the exponent of the matrix A can be calculated by the following infinite series;

$$e^{A} = \mathbf{I}_2 + \frac{1}{1!}\mathbf{A} + \frac{1}{2!}\mathbf{A}^2 + ... + \frac{1}{n!}\mathbf{A}^n + ... \tag{19}$$

with $\mathbf{I}_2$ representing the 2×2 identity matrix. Since the system of interest has; $\mathbf{A}^2 = \mathbf{0}_{(2x2)}$, the terms of equation (19) that has higher power than one can all be neglected. Hence, for a nominal second order system, one can simplify the matrix exponent given in predictive integration as follows;

$$e^{Ak} = \mathbf{I}_2 + \frac{1}{1!}\mathbf{A}k = \begin{bmatrix} 1 & k \\ 0 & 1 \end{bmatrix} \tag{20}$$

Substituting this identity for the matrix exponent and the system parameters given in (16) back to the equation (18), we can obtain the following discrete-time dynamics for the prediction of future motion:

$$\begin{aligned} \begin{matrix} q[\alpha T] \\ \dot{q}[\alpha T] \end{matrix} &= \begin{bmatrix} 1 & \alpha T \\ 0 & 1 \end{bmatrix} \begin{matrix} q[0] \\ \dot{q}[0] \end{matrix} \\ &+ \sum_{m=1}^{\alpha} \begin{bmatrix} 1 & -mT \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ \frac{K_n}{a_n} \end{bmatrix} i^{ref}[mT] \end{aligned}$$

which can be further extended as follows:

$$\begin{aligned} q[\alpha T] &= q[0] + \alpha T\dot{q}[0] - (K_n/a_n)\sum_{m=1}^{\alpha} mTi^{ref}[mT] \\ \dot{q}[\alpha T] &= \dot{q}[0] + (K_n/a_n)\sum_{m=1}^{\alpha} i^{ref}[mT] \end{aligned} \tag{21}$$

B. Predictor

We now have all means of calculating the future states of our system. In order to complete the derivation of predictor, one has to incorporate the scheme proposed in equation (14) for the term $i^{ref}[mT]$ of equation (21).

Assuming a velocity tracking control structure on the slave system and observing that the prediction is made over an envelope of $[\alpha T]$ discrete time samples (i.e. the data from αT seconds ago should be used in the predictor), one can write down:

$$i^{ref}[mT] = i^{ref}[(m-\alpha+1)T] - i^{ref}[(m-\alpha)T] \tag{22}$$

Substituting this identity back to the equation (21), one can finally obtain the m step forward velocity reference of the slave system as follows:

$$\dot{q}[\alpha T] = \dot{q}[0] + (K_n/a_n)\sum_{m=1}^{\alpha}\left(i^{ref}[(m-\alpha+1)T] - i^{ref}[(m-\alpha)T]\right) \tag{23}$$

which can further be integrated to obtain $q[\alpha T]$.

V. Experiments

A. Experimental Setup

Verification of the proposed predictor is made on an experimental setup consisting of linear motors. Two Hitachi-ADA series linear AC motors and drivers are used as the experimental platform. The linear motors had Renishaw RGH41 type incremental encoders with $1\mu m$ resolution. The implementation of the algorithm is made over C code and real time processing was enabled by a D-Space DS1103 card. The experiments are conducted with constant time delays in both measurement and control channels and the prediction is made based on the magnitude of that constant delay. A sampling frequency of 1KHz was used for the overall system. A picture of the experimental setup is provided in Fig. 2.

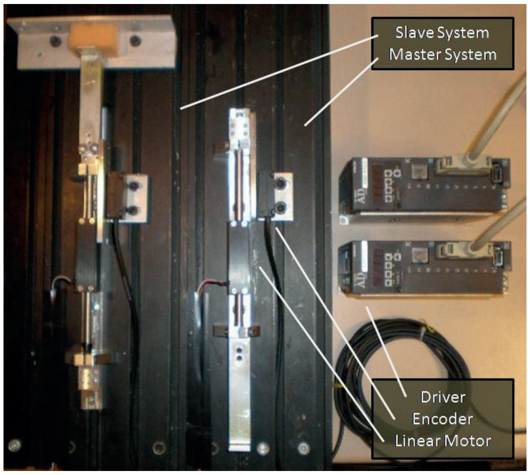

Fig. 2. Experimental Setup

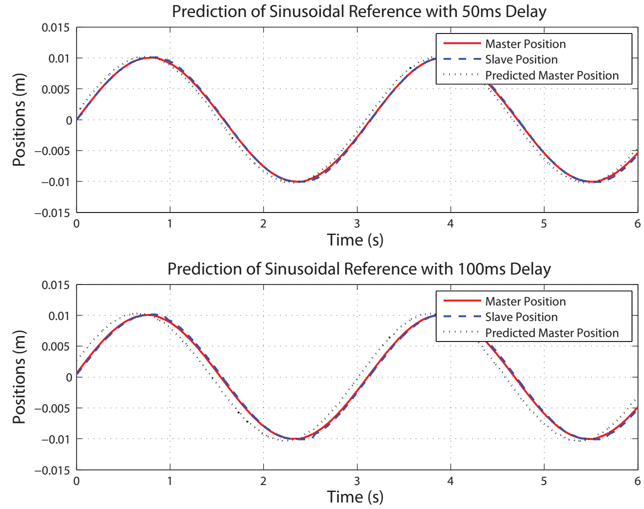

Fig. 3. System Response for Sinusoidal Reference

B. Experiment Results

The proposed predictor is tested in a series of experiments. In order to see the performance of the observer, three different sets of experiments are made. In the first two sets, computer generated references were used to drive the master system while in the third set random references generated by a human operator are used as the input of master system. Each set of experiment included one experiment with $100ms$ delay and one experiment with $50ms$ delay for all of the input channel, control channel and the predictor respectively

1) Experiment Set I (Sinusoidal Computer Reference): For this set of experiments, a computer generated reference of $sin(2t)$ is imposed on the master system. The tracking of that reference on the master manipulator is achieved via the use of DOB in the inner loop and PD control in the outer loop. In order to generate the slave system motion prediction, the velocity response from the master system is used. The results of sinusoidal system reference is shown in Fig. 3. An important fact about the sinusoidal reference is that, due to the continuous structure of motion, the overshoots are in the minimal level.

2) Experiment Set II (Triangular Computer Reference): For this set of experiments, a computer generated triangular reference with a slope of $0.02m/s$ is used on the master system. Like the sinusoidal experiments, tracking of the reference is attained by PD+DOB controller structure. In order to generate the slave system motion prediction, the velocity response from the master system is used.

Selection of triangular reference trajectory has a special purpose. Since the predictor acts like an accumulator for a period equal to the time delay, it becomes sluggish when the master system exhibits a constant velocity behavior for a long time (i.e. for a period greater than the time delay). Once this sluggish form is settled in the predictor, the reflection of the change in motion can only be seen after the period of time delay. So, unlike the sinusoidal case, in the triangular reference the change in the structure of motion creates an overshoot that is directly proportional to the slope of constant velocity regime and the amount of time delay used in the predictor. Right after the delay time, however, the predictor converges to the correct prediction of new reference and hence master-slave tracking can be achieved. The results of triangular system reference is shown in Fig. 4.

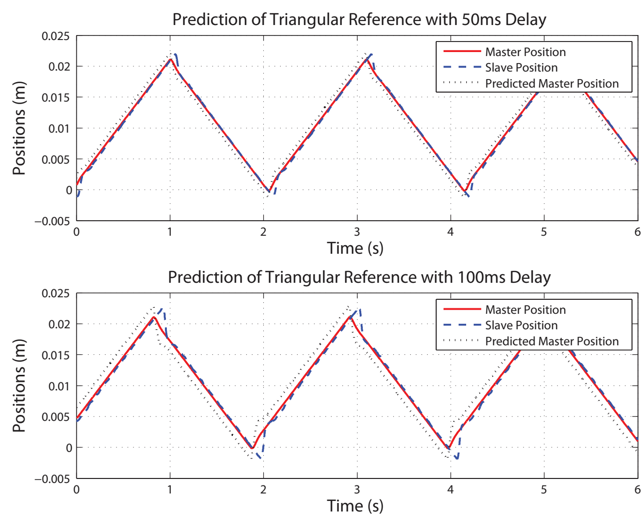

Fig. 4. System Response for Triangular Reference

3) Experiment Set III (Random Operator Reference): For this set of experiments, random references generated by a human operator is used. So, the master system is left without any computer input and the operator is allowed to move the master robot. Like the two other experiments, velocity response of the master system is used to generate the slave system motion prediction. The results of random system reference, shown in Fig. 5, clearly indicate the power of the proposed structure in predicting the motion for a predefined period of time delay.

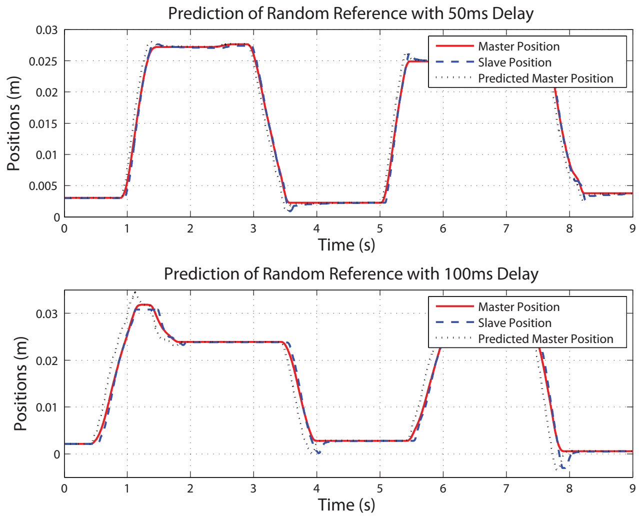

Fig. 5. System Response for Random Reference

VI. Conclusion

In this paper, a structure is proposed for the prediction of the master system motion to be used in time delayed control systems. The proposed structure makes use of the current and past system data and a discrete predictor to integrate further the system input for period equal to the time delay. Derivation of the predictor is made with the assumption of a nominal system enforced by DOB. The results obtained from the proposed structure is validated via a series of experiments including different motion structures and different amounts of time delay.

VII. Future Study

Further work is planned to investigate the implementation of the proposed predictor over a bilateral control system and carry out the corresponding analysis to have full synchronization between master and slave systems in time delayed bilateral control.

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