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# On using delay predictors in controlling force-reflecting teleoperation over the internet

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## SUMMARY

Using the notation of the wave variables, this paper introduces an autoregressive predictor, which forecasts the future values of the delay based on its previous values. Using this new knowledge, the teleoperation control system can be tuned to achieve a better and more practical performance. The validity of this modeling is first verified by actual experiments and then the results are used in simulated teleoperations.

KEYWORDS: Teleoperation; Internet time delay; Estimation; Force reflection.

## I. INTRODUCTION

The Internet is considered to be an inexpensive existing means of bilateral data communication. That is the main reason for several attempts to use the Internet in teleoperation.[1,2] However, modeling the Internet delays has always been considered to be a difficult task,[3] and lack of accurate models for the delay behavior creates some obstacles for a desirable teleoperation performance, specially if the teleoperation system includes force feedback.[2,4] The Internet has an inherent variable time delay, which challenges the development of a robust control schemes. However, several new methods have been introduced to deal with these variable delays and several new applications of teleoperation over the Internet are being investigated.

In this paper, we use a modeling/prediction approach to forecast the upcoming value of the Internet time delay. We combine this idea with the concept of wave-integral transmission used[2] and wave-integral feed-forward used[5] to tune the amount of integral feed-forward. By tuning this feed-forward gain, we can decrease the mismatch between the master and slave forces and velocities.

## II. TELEOPERATION CONTROL SCHEMES AND THE NOTION OF WAVE VARIABLES

It has been shown in reference [6] that if the force and velocity signals are transmitted as they are from the master side to the slave side and also when the measure of feedback force is available, the system will become unstable even with the smallest delays.

It was shown that if the control law is modified such that it mimics the transfer function of a passive transmission line, the total teleoperation system will remain stable even in the presence of feedback time delays.[6] One of the methods of dealing with time-delayed teleoperation with force-feedback is using wave variables. It has pointed out[7] that the main cause of instability in force-feedback teleoperations with time delays is the non-passive nature of the communication lines. Using some ideas from the scattering theory, he suggested to modify the control law to make the system transfer function appear like that of a passive transmission line. The concept of 'Wave variables' has been proposed[8] by redefining the system power flow. Usually, the power flow is defined as the product of an effort and flow pair.

Let $\mathbf{F}$ be the force applied to a system and $\dot{\mathbf{x}}$ be the velocity of motion in that part of the system. To introduce the wave variables $\mathbf{u}$ and $\mathbf{v}$, we assume two streams of power moving in opposite directions in the system. This means we have divided the power flow to a stream going from the master side towards the salve side (positive direction) $((1/2)\mathbf{u}^T\mathbf{u})$ and a stream going from slave to master $((1/2)\mathbf{v}^T\mathbf{v})$. In other words, we assume that the master side is always giving energy to the system. This given energy might become negative at instants, meaning that the power transfer is actually from slave to master. Therefore, we can redefine the power flow as: $P = \dot{\mathbf{x}}^T\mathbf{F} = (1/2)\mathbf{u}^T\mathbf{u} - (1/2)\mathbf{v}^T\mathbf{v}$. Using this equation we assume that $\mathbf{u}$ and $\mathbf{v}$ to be linear combinations of $\dot{\mathbf{x}}$ and $\mathbf{F}$ or

$$\mathbf{u} = m_1 b\dot{\mathbf{x}} + n_1\mathbf{F}$$
$$\mathbf{v} = m_2 b\dot{\mathbf{x}} + n_2\mathbf{F}$$

The factor of b is a wave impedance and is used in teleoperation to balance between force and velocity. These equations can further be simplified as:

$$\mathbf{u}(t) = (b\dot{\mathbf{x}}(t) + \mathbf{F}(t))/\sqrt{2b} \quad \mathbf{v}(t) = (b\dot{\mathbf{x}}(t) - \mathbf{F}(t))/\sqrt{2b} \tag{1}$$

The tuning parameter $b$ acts as a weight function and changes the relative magnitude of $\dot{\mathbf{x}}$ and $\mathbf{F}$ with respect to each other. Any pair of the above variables $(\mathbf{u}, \mathbf{v}, \dot{\mathbf{x}}, \mathbf{F})$, can be selected as input or output variables. Equations similar to (1) have been widely used in scattering theory and communication channel designs, where a waves in opposite directions coexist. Figure 1 shows details of the overall control block diagram used in the study of this paper.

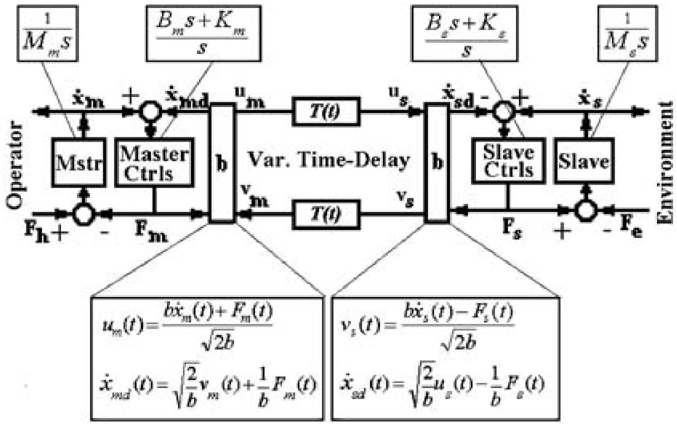


Fig. 1. The overall control block diagram which was used in the study of this paper.

## III. MODELING AND PREDICTION

*III.1. Model derivation*

In this section we treat the variable time delay as a stochastic process and will derive a mathematical model for the delay behavior. Several model types can be used for stochastic processes. Among them the Autoregressive(AR) model, the Moving Average Model (MA) and the Autoregressive-Moving Average (ARMA) models are widely used.

The autoregressive model gives the future values of a stochastic process in terms of its past values explicitly. The simplicity of the AR model lies in the fact that model values can be defined by solving a single matrix equation called the Yule-Walker equation.[9]

An autoregressive (AR) process is a process whose values at time $n$ depend on its values at times $n-1, n-2, \ldots$ through

$$x[n] = \sum_{i=1}^{N} a_i x[n-i] + w[n] \tag{2}$$

where $x[n]$ is the signal we want to model and $N$ is the order of our AR model, which can be selected as a design parameter. $N$ is the number of past values we observe before predict $x[n-i]$s are the past $N$ observed values of the signal and $a_i$s are constant coefficients relating $x[n]$ to $x[n-i]$s. $w[n]$ is white noise with autocorrelation

$$E[w[n]w^*[n]] = \sigma_w^2 \delta[n] \tag{3}$$

where $*$ indicates complex conjugate, $\sigma_w^2$ is the variance of the noise, $\delta[n]$ is the discrete delta function and the operator $E[]$ takes the expected value of the parameter appearing between its brackets.

For our model to be useful for teleoperation performance, the delay should be measured over the Internet link connecting the master manipulator and the slave manipulator. We assume that those two manipulators are connected to computers having fixed IP addresses over the Internet. Our experiment consists of sending $N$ packets from the master computer to the slave computer at each probing. The packets are sent using the Internet control message Protocol (ICMP)

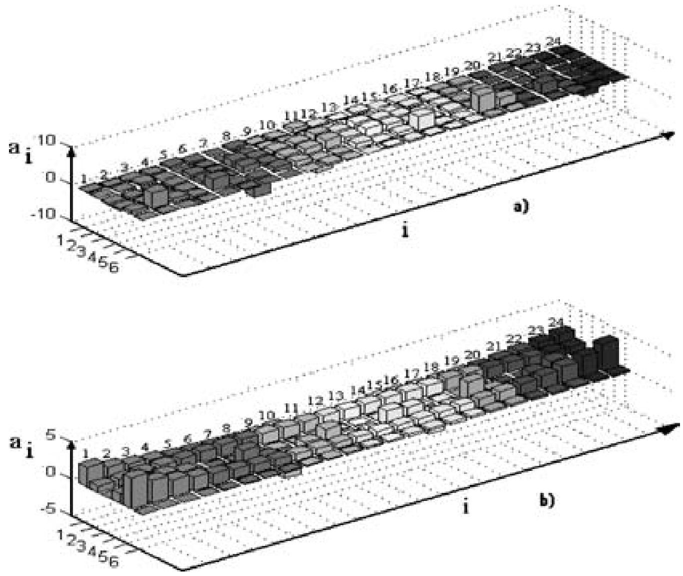


Fig. 2. (a) The delay model parameters for the server www.dci.co.ir (b) The delay model parameters for the server leland.stanford.edu. The values of the model parameters ($a_i$s) are plotted vs. the model parameter index i and the experiment index for the 6 times the experiment took place during the day.

and the ping utility.[10] The packets are then echoed back by the slave computer to the master computer. The round trip time delay (RTT) can be read from the packet header, which includes the time the packet has been traveling.

*III.2. Experiments and measurements*

Our experiments were based on data gathered from a number of different connections between a computer in our laboratory and computers in locations as widespread as Stanford CA, Data Communication Incorporation (DCI) Tehran Iran, UBC Vancouver.[10] The delays of these links were measured using the Microsoft 'Ping' utility at 6 different times during the day. These probing times are Each time 24 measurements were made and the results were given to order-24 autoregressive model such as the one described in the previous section. The model parameters for two servers on a certain day are plotted in Figure (2).

The developed model was then used to predict the future values of the delay in a way similar to the above example. The following results are examples of our experiments performed with Data Communication Incorporation (DCI) Tehran, Iran. The results for a certain week are plotted in Figure (3) as an example. Except for a case of failure of the remote site computer, the error between the measured and predicted values never exceeded 20% (Figure 3b).

## IV. TELEOPERATION SIMULATIONS

In Figure (1), the Operator at the left side is the human operating with the system. In simulations, the human is modeled by a force source, which applies a step force ($F_h$) to the master manipulator. The Master system consists of the dynamics of the master manipulator ($(1)/(M_s s)$) and may also include a PD controller to determine the speed of motion based on the operator force input and the force feedback. The Force and velocity of the master system are then given

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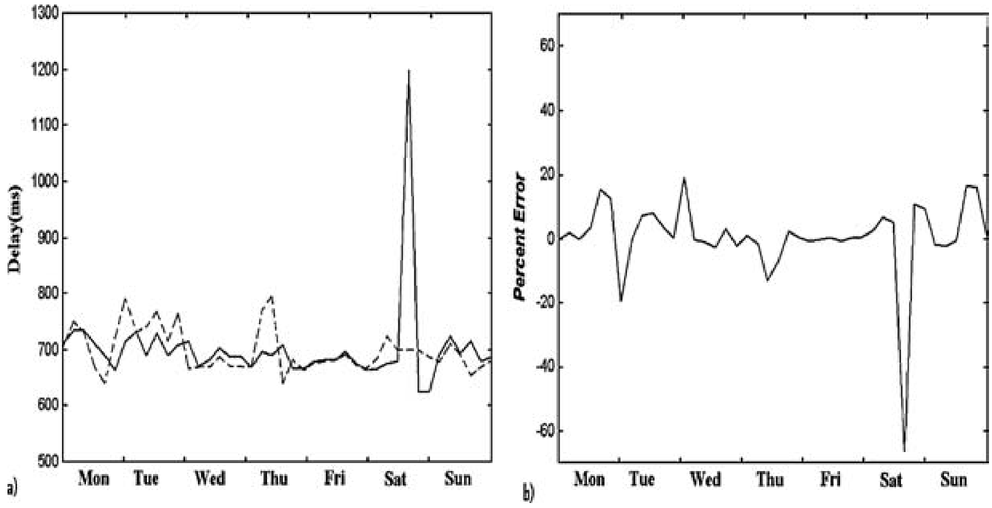


Fig. 3. (a) The predicted (dashed) and measured (solid) delay values for the server www.dci.co.ir during one week (b) The prediction error for www.dci.co.ir during one week.

to the master side wave-transformer. The master side wave-transformer, converts the force $F_m(t)$ and the velocity $\dot{x}_m(t)$ into the wave variable $u_m(t)$ and decodes the feedback wave variable $v_m$, to be discussed shortly, into the feedback force and velocity signals.

The wave variable $u_m(t)$ is then transmitted through the communication line to the slave side. The communication line is assumed to introduce the variable time delay of $T(t)$ into the control system. In our experimental studies, the delay is random process with a exponential distribution at close distances (e.g. S.F.U. to Stanford) and close to normal distribution at large distances (e.g. SFU to DCI). The normal distribution is used in our simulations as a statistical model for the Internet delay.

### IV.1. Prediction and gain tuning

There are a number of parameters in the basic teleoperation system that affect the performance. These parameters are the wave-impedance, the damping/spring parameters of the master controller and the damping/spring parameters of the slave controller. A preliminary study such as Figure (4) on the average force and velocity errors shows that as stated in reference [11], changing the value of the wave impedance $b$ is only a tradeoff between force matching and velocity matching. Therefore, the value of $b$ should be chosen based on the task in hand, rather than the value of the delay. Similarly, the controller parameters on the master and slave controllers have little to do with the amount of the delay, and are to be chosen based on the nature of the teleoperation environment.

One performance improvement strategy suggested by previous researchers is transmitting wave integrals. Reference [2] had suggested to transmit the wave integrals along with the wave variables themselves to improve the teleoperation performance. They suggested using a filter to obtain the $u_{out}$ from the integral of the wave variable $E(t) = \int u dt$ and the integral of the square of the wave variable $U(t) = \int u^2 dt$

$$u_{out}(t) = \begin{cases} \alpha \frac{E(t)}{U(t)} & if \quad U(t) \neq 0 \\ 0 & if \quad U(t) = 0 \end{cases} \tag{4}$$

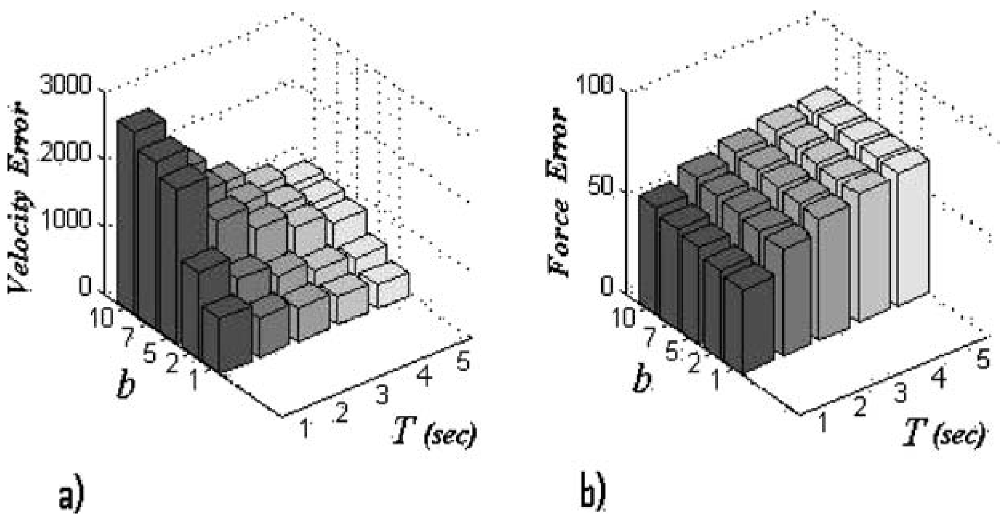


Fig. 4. Effect of changing the parameter $b$ on velocity error shown in (a) and on the force error shown in (b).

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However, the zero threshold level would be violated by the slightest noise in the system and therefore their filter, although mathematically correct, is not functional in practice. Using a more realistic noise margin instead of zero at the criteria will result in a more practical filter.

The idea of transmitting wave integrals was further investigated in reference [5]. They suggested that the integral of the master side wave variable ($u_m$) should be calculated numerically up to the time of each transmission and then should be sent along to the slave side.

Similarly at the slave side, the integral of the received wave variable $\hat{u}_s(t)$ is calculated and is then compared with the value of the integral received from the master side, which is calculated numerically. The difference ($\Delta$), which can be interpreted as a measure of change in energy of the signal, will be fed back to $\hat{u}_s$ to restore the lost energy.

$$\Delta(t) = \int u_m(t) - \int \hat{u}_s(t)$$

[5] had mentioned the importance of the gain of this feedback and had mentioned that the value of the gain should be chosen such that the system is well compensated, but at the same time not to sensitive to disturbances. The simulations showed that the optimal value of this gain, hereafter called $\sigma$, is to obtain the smallest error varies as the time delay is changed. This feedback gain, or $\sigma$, is the parameter we have chosen to tune with our knowledge of the delay.

$$u_s(t) = \hat{u}_s(t) - \sigma\Delta(t) = u_s(t) - \sigma\left(\int u_m(t) - \int \hat{u}_s(t)\right) \tag{5}$$

Let us assume that there is no scaling between the master and slave sides, in other words the master and slave manipulators are identical. We define the force error to be the maximum mismatch between the forces at the master side and the slave side.

$$F_{err} = max\,\{F_m(t) - F_s(t - T(t))\} \tag{6}$$

The velocity error is similarly defined as the maximum mismatch between the velocities at the master side and the slave side.

$$\dot{x}_{err} = max\,\{\dot{x}_m(t) - \dot{x}_s(t - T(t))\} \tag{7}$$

Our simulations show that for every value of $T$, there is a value of $\sigma$ to minimize the error.

Figure (5) shows the behavior of the above mentioned errors with changes in $T$ and $\sigma$. It can be seen that for every value of $T$, the value of $\sigma$ can be chosen such that the error is minimized. For each $T$ in Figure (5), the top surface of one of the error bars is painted black to show the optimal value of $\sigma$. In the same figure, the hatched squares show

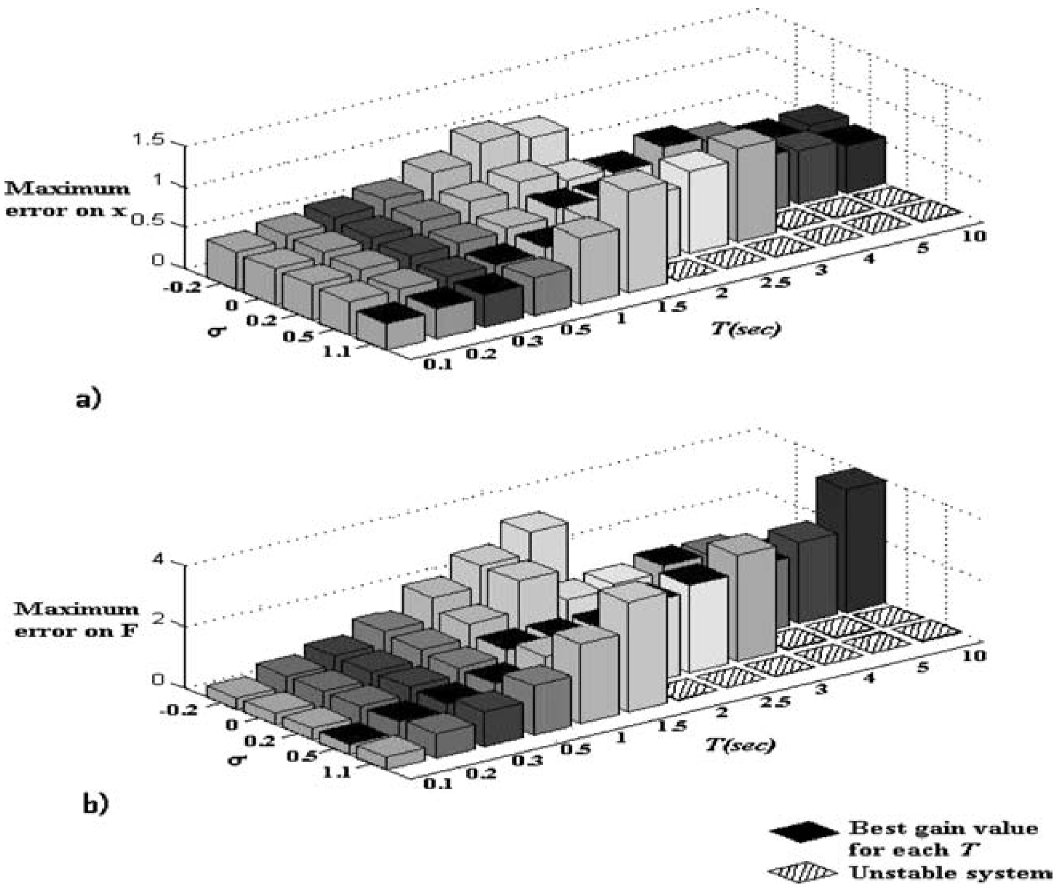


Fig. 5. The effect of tuning $\sigma$ on the (a) velocity and (b) force errors.

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some limitations, where the system becomes unstable due to the choice of an improper $\sigma$. At those values of $\sigma$ the amount of energy fed to the system for compensation is more than necessary and that makes the system non-passive and unstable.

When operating, the delay predictor will estimate the future value of the delay. This estimated value of $T$ is then used by the gain scheduler to search in a look-up table like Figure (5) to find the optimal value of the gain $\sigma$. As the value of the delay changes, the system will follow the path of black-painted squares (hereafter called the $\sigma$-path) to the predicted delay and finds the value of $\sigma$ that gives the smallest error.

Therefore, when the future value of the delay is predicted, we can use a look-up table similar to the black-painted $\sigma$-path in Figure (5) to re-tune the system. This way choosing the optimal value of $\sigma$ can minimize our error on force or velocity, or sometimes both. When dealing with large delays the value of $\sigma$ has to be set to zero, to guaranty the passivity of the system and to keep stable operation.

## V. CONCLUSIONS

Introducing a delay predictor in a wave-based teleoperation system can improve the performance through feedback of the integrals of the wave variables. By tuning the value of the feedback gain for the integrals, some of the lost properties of the signal can be restored the overall delay can be reduced for force-precision or velocity-precision tasks.

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