A Bilateral Control of Teleoperators Based on Time Delay Identification

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***Abstract*—In this paper, passivity and wave variables are first introduced, and then the reasons of communication time-varying delay are analyzed. For this time-varying delay a new-type time delay identification method based on the cross-correlation technology is proposed and this method can converge the time-varying delay parameter quickly. Finally this method is combined with wave integrals and a control scheme is proposed especially for time-varying delay. The effectiveness of the proposed method has been demonstrated through the simulation results.**

***Keywords*—wave variables, wave integrals, time-varying delay, identification**

I. Introduction

Master-slave manipulators are often used for teleoperation in hazardous environment. Control laws for master-slave manipulators are either unilateral (without force reflection) or bilateral (force reflecting). Force feedback in bilateral control improves the performance of teleoperation in most cases.

When the slave site is located far from the master site, communication delay between the two sites is not negligible. For example, communication delay between a ground station and a space robot in a satellite orbit is 3-6 seconds[1]. When we use a conventional bilateral control law, such as symmetric type or force reflection type, even a small communication delay may easily destabilize the system. A stable control method under the communication delay was developed by Anderson and Spong[2], and studied further by Niemeyer and Slotine[3]. These methods are based on wave variables instead of the conventional power variables, i.e., velocity and force. Wave variables present an extension to the theory of passivity which creates robustness to time delay.

The above-mentioned methods all focus on the constant delay. However, the time delay often fluctuates when the controlled system is the space-based, internet-based or underwater telerobot. For the communication time-varying delay a lot of scholars have done a large amount of work, the representative one is wave integrals theory proposed by Niemeyer and Slotine [4,5], the main idea of wave integrals theory in [4,5] is to transmit the wave variable integrals along with the original wave variables and propose a reconstruction filter to stabilize the system. Yokokohji, Imaida and Yoshikawa have developed wave integrals theory and solved the problem caused by the time-varying delay by proposing the compensator both on the master side and the slave side[6,7]. Mirfakhrai and Payandeh in reference [8] have created the time-varying delay model by AR model, and used the AR model for the delay prediction application, and proposed a method of the feedback gain .

In this paper we adopt the wave integrals to solve the problems caused by time-varying delay, which follows the structure of reference [8], but introduces a new-type time delay identification method[9-12]. The paper is organized as follows: Section 2 simply introduces passivity and wave variables, and the effectiveness of wave variables for the constant delay. Section 3 explains the reasons of the time-varying delay and the problems caused by the time-varying delay, and demonstrate that the conventional wave variables can not solve the problems caused by the time-varying delay. Section 4 proposes an identification method for time-varying delay based on the cross-correlation technology, and combines it with wave integrals to propose a method for the time-varying delay. The simulation results show the effectiveness of the method. Finally section 5 includes some concluding remarks and future work.

II. Wave Variables[2,3]

Wave variables present a modification or extension to the theory of passivity. They are also closely related to the scattering and small gain theories. Based only on the concepts of power and energy, they are applicable to nonlinear systems and can handle unknown models and large uncertainties. As such they are well suited for interaction with real physical environment.

To achieve their goals, wave variables provide an alternate information encoding scheme to the standard power variables. The required transformations are extremely simple and preserve all information.

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A. Passivity

One of main reasons for introducing wave variables is their effect on the condition for passivity. An n-port is said to be passive if and only if for any independent set of n-port flows v_i inject into the system, and efforts F_j applied across the system

$$\int_0^{\infty} F^T(t)v(t) \geq 0 \tag{1}$$

where $F=[F_1,F_2,\cdots,F_n]^T \in L_2^n(R_+)$ and $v(t)=[v_1,v_2,\cdots,v_n]^T \in L_2^n(R_+)$.

It is assumed that the system is relaxed, i.e., no initial loading exists on any of the springs in the system, and none of the inertias have an initial velocity.

Condition (1) is simply a statement that a passive n-port may dissipate energy but cannot increase the total energy of a system in which it is an element.

Now we use the definition of the passivity in the teleoperation. In the teleoperation the power flow is defined as

$$P_{in} = \dot{\mathbf{x}}^{\mathrm{T}}\mathbf{F} \tag{2}$$

where $\mathbf{F}$ is force or torque, $\mathbf{x}$ is velocity or position.

In the power domain passivity is tested by

$$\int_0^t P_{in}\, d\tau = \int_0^t \dot{\mathbf{x}}^{\mathrm{T}}\mathbf{F}\, d\tau \geq -E_{store}(0) \quad \forall t \geq 0 \tag{3}$$

where $P_{in}(t)$ is the power input and $E_{store}(0)$ denotes the initial stored energy.

We can see in (3) passivity depends on the both variables. If the output variable is delayed, the effect on the product and thus passivity is unpredictable. So wave variable is developed.

B. Wave variables

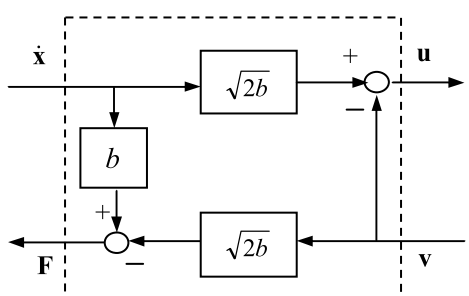

Figure 1. Wave variable transformation

The key feature of wave variables is their encoding of velocity and force information. In particular, we define

$$\mathbf{u} = \frac{b\dot{\mathbf{x}}+\mathbf{F}}{\sqrt{2b}} \qquad \mathbf{v} = \frac{b\dot{\mathbf{x}}-\mathbf{F}}{\sqrt{2b}} \tag{4}$$

here $\mathbf{u}$ denotes the forward or right moving wave, and $\mathbf{v}$ denotes the backward or left moving wave. The characteristic wave impedance b is a positive constant or a symmetric positive definite matrix and assumes the role of a tuning parameter, which allows matching a controller to a particular environment or task.

After wave variable, equation (2) becomes

$$P_{in} = \dot{\mathbf{x}}^{\mathrm{T}}\mathbf{F} = \frac{1}{2}\mathbf{u}^{\mathrm{T}}\mathbf{u} - \frac{1}{2}\mathbf{v}^{\mathrm{T}}\mathbf{v} \tag{5}$$

and equation (3) becomes

$$\int_0^t \frac{1}{2}\mathbf{v}^{\mathrm{T}}\mathbf{v}\, d\tau \leq \int_0^t \frac{1}{2}\mathbf{u}^{\mathrm{T}}\mathbf{u}\, d\tau + E_{store}(0) \quad \forall t \geq 0 \tag{6}$$

Not surprisingly a system is passive if the energy in the outgoing wave $\mathbf{v}$ is limited to the energy provided by the incoming wave $\mathbf{u}$ or stored initially.

After wave variables, passivity compares only the integrated magnitudes. If the output variable is delayed, its power is temporarily stored without changing the passivity. For example, consider a simple delay

$$\mathbf{v}(t) = \mathbf{u}(t-T) \tag{7}$$

The passivity condition (6) is satisfied and the stored energy is computed as

$$E_{store}(t) = \int_{t-T}^{t} \frac{1}{2}\mathbf{u}^{\mathrm{T}}\mathbf{u}\, d\tau \tag{8}$$

which store the input power for the duration of the delay. We can see from (8) the passivity is independent to the time delay T.

So all systems, which are passive in the power variable notation, remain passive after transformation into wave variables. In addition, time delays are now also passive elements. So systems expressed in wave variables become completely robust to delays of any amount.

C. Simulations

In order to verify the validity of the wave variables, we have done the following simulation. We adopt the modeling of master-slave systems as Fig.1 in the reference[9], in it the controller are all PD controllers on the master and slave side and the system input is square wave signal, the force feedback gain is. $K = 1[1/s]$ The results are shown in the three following figures. Fig.2 shows the perfect control result when using the conventional bilateral control method without communication delay. One can see that the slave arm can easily track the master arm. Fig.3 shows both master arm and slave arm are all instable with the time delay. Fig.4 shows that the system is also stable with time delay by using wave variables and the slave arm can track the master arm perfectly.

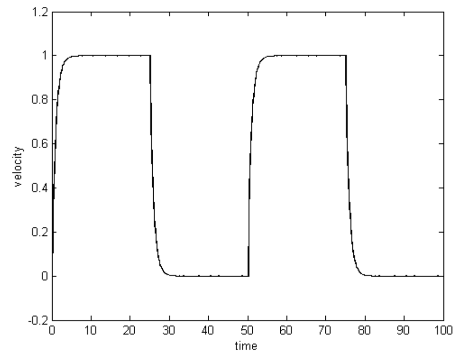

Figure 2. Without time delay

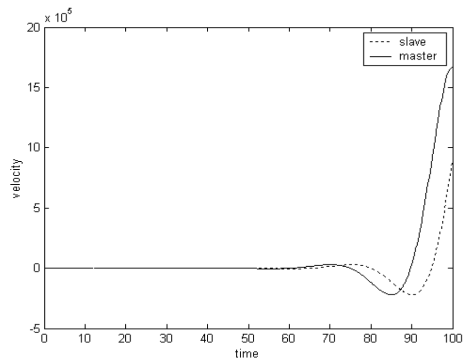

Figure 3. $\tau = 5$ without wave variables

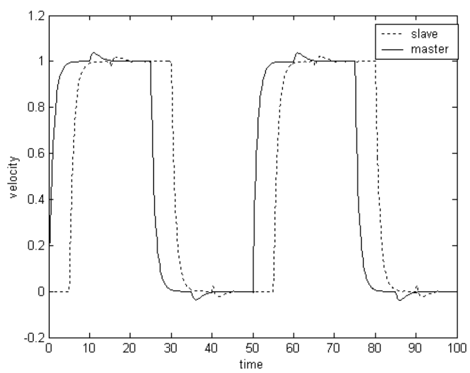

Figure 4. $\tau = 5$ withwave variables

III. TIME-VARYING DELAY

A. Reasons of time-varying delay

When we use a computer network for the communication line between the master and the slave, time delay is not constant but it fluctuates. There are two mainly reasons.

First, variable delays are due to motion of the slave systems. For instance, space-based or underwater telerobotic applications involve moving vehicles and thus experience changing transmission times to and from the stationary operator. The resulting variations, however, are typically very slow and in practice can often be ignored.

Second, and significantly more interesting, are rapidly and possibly randomly varying transmission delays. This is the case, for instance, in satellite-based transmission through varying relay sites. Perhaps more intriguingly, this is also the case in the Internet, which has frequently been suggested as a means for creating teleoperation systems between a variety of remote sites, given the availability of ever less expensive force-reflecting interfaces. Information is transmitted in data packets and the packets are transmitted through several computer nodes before reaching the purpose address. Each node deals with and queues the packets from different source and route them to the node closest the purpose. If a node overloads, will lose some incoming packets or to a little fewer nodes. In this way, unpredictable delay is introduced in the dataflow, and the delay increase with the distance and change with the routing nodal quantity and each nodal transmission tactics.

B. Problems caused by time-varying delay

When the communication delay fluctuates the result is the distortion of waveform shown as the following figure. Here, input signal is sine signal and time delay is step signal plus sine signal. Shown as Fig.5, when the delay time is increased, the waveform is stretched. In an extreme case when the delay time becomes very large instantaneously, which is so called a "blackout" phenomenon, the output wave becomes constant until the next wave arrives. On the other hand, when the delay time decreases, the data is compressed. In an extreme case, several wave variables arrive at the same time like a shock wave.

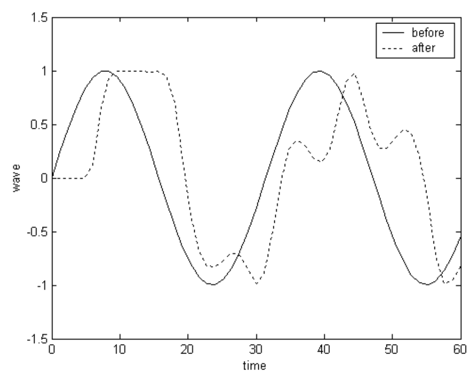

Figure 5. Distortion of waveform due to a fluctuating time delay

If we don't adopt any measures with the time-varying delay, the system may become unstable. Here the simulation system is similar to the above section, but the time delay fluctuate ranging between 5s to 6s shown as Fig.6, the velocity responses of the master arm and the slave arm are shown as Fig.7. From Fig.7 we can see the system become unstable when the time delay fluctuates.

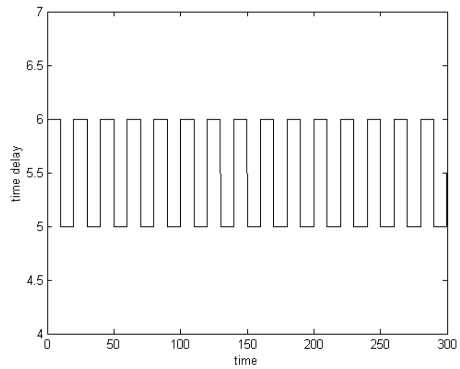

Figure 6. Time delay τ

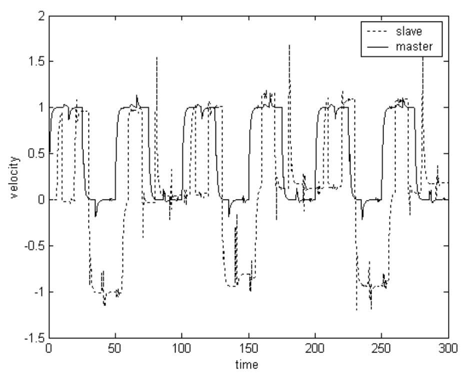

Figure 7. Velocity responses when time delay fluctuates

IV. TIME DELAY IDENTIFICATION[9-12]

An identification method based on the cross-correlation technology is proposed in this paper. By defining the performance function——the correlation function between the process output and the model output and maximizing it the time delay is identified online.

A. Time delay identification principle

Consider two measurement signals received at two sensors, the two signals are transmitted from the same source $s(t)$. One of the signals, $x_2(t)$, includes a time delay τ. The physical problem can be mathematically described as:

$$\begin{aligned} x_1(t) &= s(t) + n_1(t) \\ x_2(t) &= s(t-\tau) + n_2(t) \end{aligned} \tag{9}$$

or in discrete-time form as

$$\begin{aligned} x_1(i\Delta t) &= s(i\Delta t) + n_1(i\Delta t) \\ x_2(i\Delta t) &= s(i\Delta t - \tau) + n_2(i\Delta t) \end{aligned} \tag{10}$$

where i is an integer and Δt is the sampling period, in order to simply and universalize the problem we assume the time delay τ is a multiple of Δt.

Many methods are employed to estimate the time delay. The basis idea of the methods is to detect the location of the correlation peak of the two received signals. To make the problem mathematically treatable, it is assumed that the noises, $n_1(t)$ and $n_2(t)$, are not correlated with each other nor with the source signal $s(t)$. It is further assumed that observation time is large compared to time delay τ and that all signals and noises are stochastic and stationary with zero-mean Gaussian distributions. A measure of correlation between the received signals is defined by:

$$R_D(\hat{\tau}) = E\{x_1(t)x_2(t+\hat{\tau})\} = R_{ss}(\hat{\tau} - \tau) \tag{11}$$

where $E\{\ \}$ denotes the mathematical expectation of the quantity within the bracket and $R_{ss}(\hat{\tau} - \tau) = E\{x_1(t)x_2(t+\hat{\tau})\}$ is the autocorrelation function of $s(t)$. $R_{ss}(\hat{\tau} - \tau)$ has its maximum value at $\hat{\tau} = \tau$. The computation of $R_D(\hat{\tau})$ requires an integration that is difficult to obtain on-line and in real-time. An identification of $R_D(\hat{\tau})$ from the sampled time series data of $x_1(t)$ and $x_2(t)$ is

$$R_D(\hat{\tau}) = \frac{1}{N}\sum_0^{N-1} x_1(i\Delta t)x_2(i\Delta t + \hat{\tau}) \tag{12}$$

where $N > 0$ is the number of sample pairs. It is required the observation time is larger than N.

B. Time delay identification

Time delay identification principle may be applied to obtain an identification of the time delay for the standard Smith predictor.

The controlled system transfer function is

$$\frac{Y(s)}{U(s)} = e^{-\tau s} \tag{13}$$

we can gain

$$Y(s) = \exp(-\tau s)U(s) \tag{14}$$

where $Y(s)$ is the system output, $U(s)$ is the system input, τ is the time delay, i.e. the parameter which need to be identified.

The identification model transfer function is

$$\frac{\hat{Y}(s)}{U(s)} = e^{-\hat{\tau} s} \tag{15}$$

then

$$\hat{Y}(s) = \exp(-\hat{\tau} s)U(s) \tag{16}$$

where $\hat{Y}(s)$ is the identification model output, $U(s)$ is the system input, $\hat{\tau}$ is the time delay identification

Assume

$$Y^*(s) = U(s) \tag{17}$$

then $y^*(t)$, $y(t)$ and $\hat{\tau}$ can be viewed as $x_1(t)$, $x_2(t)$ and τ. The identification $\hat{\tau}$ of τ can be obtained by maximizing the correlation function $R_D(\hat{\tau}) = E\{|y^*(t)y(t+\hat{\tau})|\}$.

$R_D(\hat{\tau})$ can be computed from the sampled time series data of $y(t)$ and $y^*(t)$

$$R_D(\hat{\tau}) = \frac{1}{N}\sum_{I_0}^{I_1} y^*(i\Delta t)y(i\Delta t + \hat{\tau}) \qquad (18)$$

where $I_1 = (t-\hat{\tau})/\Delta t$, $I_0 = I_1 - N + 1$. It is apparent that $I_0 > 0$. This implied that $t \geq (N-1)\Delta t + \hat{\tau}$ has to be met for any selected N, or $N \leq (t-\hat{\tau})/\Delta t + 1$ for any given observation time t.

C. *Wave integrals*

In this paper, we adopt the configuration of the reference [8] shown as the following figure.

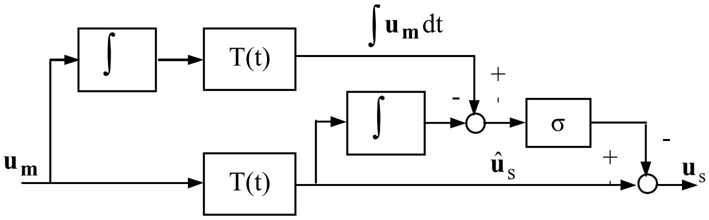

Figure 8. Wave integrals

The detail meanings of the variables can be seen in the reference [8].

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

Δ can be interpreted as a measure of change in energy of the signal, and will be fed back to $\hat{\mathbf{u}}_s$ to restore the lost energy. Δ is added to the received wave variable, ($\hat{\mathbf{u}}_s$), amplified by a certain gain, hereafter called σ. Finally we calculate the slave wave variable as:

$$\begin{aligned} \mathbf{u}_s(t) &= \hat{\mathbf{u}}_s(t) - \sigma\Delta(t) \\ &= \mathbf{u}_s(t) - \sigma\left(\int \mathbf{u}_m(t) - \int \hat{\mathbf{u}}_s(t)\right) \end{aligned} \qquad (19)$$

Yokokohji etc. [8] mention that the value of the feedback gain (σ) should be chosen such that the system is well compensated, but at the same time not too sensitive to disturbances. However, they do not suggest a practical way to tune this gain. From the simulation, we know the gain σ should vary with the time-varying delay in order to obtain the smallest error. Namely, at every value of the time-varying delay, the error between the master arm and the slave arm can be minimized if the magnitude of σ is chosen accordingly. Concretely σ should be negative if the time delay becomes large and σ should be positive if the time delay becomes small, but the magnitude of σ should be smaller. So, if we have the time-varying delay identification value, we can obtain the gain σ.

D. *Simulation results*

Finally the structure figure of the system is shown as the Fig.10. The simulation system is similar as the section 3 where the time-varying delay is the step signal plus square signal. The simulation results are shown as Fig.9.

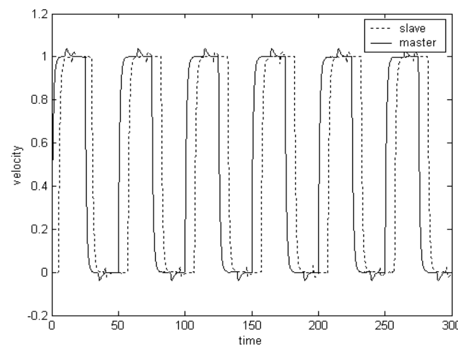

Figure 9. Velocity responses with time-varying delay by using wave integrals

Comparing the Fig.9 with the Fig.7, we can conclude the time delay identification plus wave integrals method can solve the problem caused by the time-varying delay and the slave arm can track the master arm perfectly.

V. CONCLUSION AND FUTURE WORK

In this paper a control method for master-slave systems based on the time-varying delay identification plus wave integrals is proposed, and the method can effectively solve the influence of time-varying delay to the stability of the systems. Simulation results have shown our control method is valid. It can be also found that the performance of the systems relates to the precision of the time-varying delay identification and the magnitude of gain σ. So, the future research point is how to improve the accuracy of the time-varying delay identification and how to provide the gain σ theoretically.

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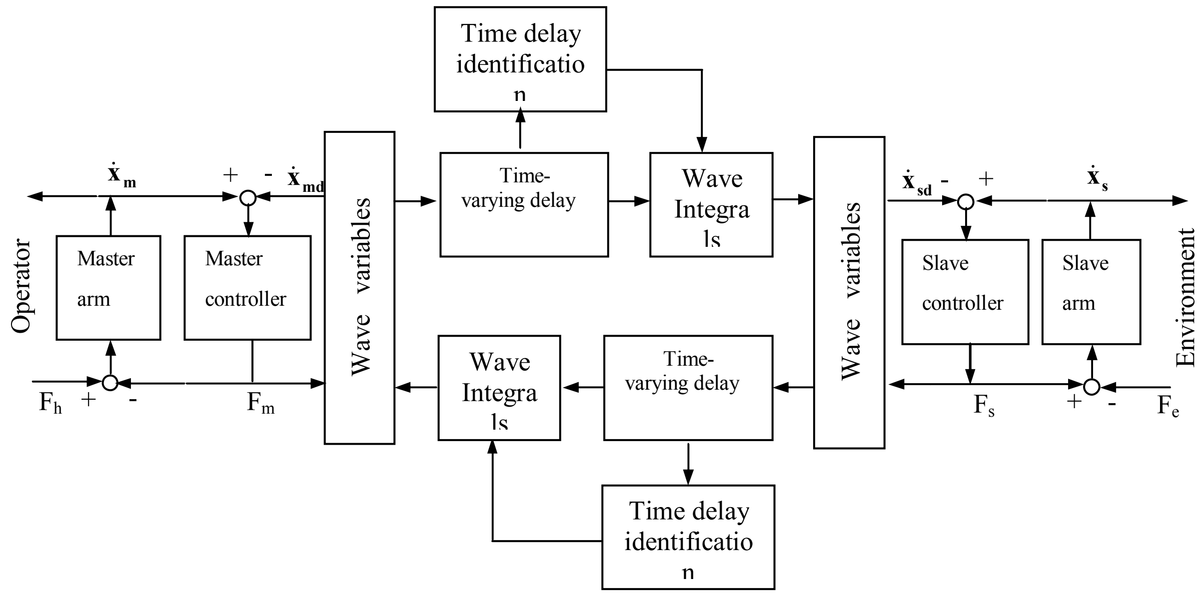

Figure 10. Structure of the system