

A STUDY on MULTIPLE DEGREE-of-FREEDOM FORCE-REFLECTING TELEOPERATION with CONSTANT and VARIABLE TIME DELAYS

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ABSTRACT

This article studies the stability and performance of teleoperation systems under the effect of constant and variable time delays by employing the wave variable method. In particular, the effect of wave variables on the stability of a multi-degree-of-freedom force-reflecting system is demonstrated on a three-axis robot and initial simulation results are presented. Also, the multi-degree-of-freedom teleoperation system model developed in the Matlab[®] environment is described. This model, used in numerical simulations, will also be utilized in real-time implementation of the controller, which is under development. System stability and instability issues are addressed especially when variable time delays are introduced. Finally, in order to insure system stability, the adaptive gain method is described as a potentially effective tool to overcome instability.

INTRODUCTION

Teleoperation is a robotics application where there is a master and a slave system interacting with each other and with their environment. The master system is often a joystick or a duplicate of the slave system that is driven by the operator. The slave system is the robot that is within a distance from the master system, controlled by the commands sent by the master system and is interacting with the environment that it is working on. There are two main types of teleoperation as unilateral and bilateral teleoperation. In unilateral teleoperation, no feedback is provided from the slave to the master and the slave is driven with the commands sent from the master. In bilateral teleoperation, any kind of feedback from the slave to the master can be sent. This feedback can be visual, force, sound, position, etc. In this study, I considered only the force-feedback bilateral teleoperation, or force-feedback teleoperation. In force-feedback teleoperation, as it was the case in unilateral teleoperation, the slave system is driven with the commands sent from the master system. But this time, slave system sends back the force-feedback information that it produces while interacting with the environment that it is working on, to the master system to make the operator that is in interaction with the master feel the environment that the slave is working on.

The common short come of the force-feedback teleoperation is the instability that the system undergoes when it experiences time delay in the communication between the master and the slave. The magnitude of this time delay could be in the order of seconds, minutes, hours or days due to the task of the teleoperation. This problem has been studied by many researchers, but Anderson and Spong were perhaps the first to use the wave variable method to control bilateral controllers [4]. Also, Niemeyer and Slotine [5], and Munir and Book [1, 2] have implemented this method to teleoperation systems. Current studies are on the variable time-delayed teleoperation [6]. Although wave variable technique guarantees stability for the constant time-time delayed teleoperation, the system experiences instability when the time delay varies.

This paper is outlined in the following manner: The next section presents a brief description of the wave variable method for single degree-of-freedom systems. Also in this section, the transition to multiple degree-of-freedom (DOF) systems is described. The following section introduces the modification made to the wave variable technique to guarantee stability for variable time-delayed teleoperation. The next section presents the modeling of a three degree-of-freedom teleoperation system using Matlab[®]. Descriptions of various Matlab[®] blocks used in the construction of master (joystick) and slave (remote system) sub-systems are provided to orient the reader to Matlab[®] modeling. Subsequently, the implementation of wave variable method to a multi-DOF system is illustrated on a three-DOF teleoperation system in Simulation Results. The legacy of the wave variable method for multi-DOF teleoperation is discussed by presenting the simulation results with and without the wave variable technique for three different time delays. Then it is shown that the teleoperation system goes unstable even though the wave variable technique is used for the variable time delayed teleoperation. Modified version of the wave variable technique is used and the simulation results are presented to overcome this instability introduced because of the variable time delay. Lastly, conclusions and planned future work appear in Section 6.

THE WAVE VARIABLE METHOD for CONSTANT TIME-DELAYED TELEOPERATION

The block diagram in Figure 1 below presents the wave variable technique in terms of the scattering transformation – a mapping between the velocity and force signals, and the wave variables [3].

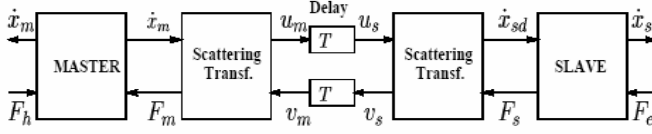


Figure 1. Scattering transformation for teleoperation with constant time delay

This transformation using the notation in [2] is described as follows:

$$\begin{aligned} u_s &= \frac{1}{\sqrt{2b}} (b\dot{x}_{sd} + F_s) \\ u_m &= \frac{1}{\sqrt{2b}} (b\dot{x}_m + F_m) \\ v_s &= \frac{1}{\sqrt{2b}} (b\dot{x}_{sd} - F_s) \\ v_m &= \frac{1}{\sqrt{2b}} (b\dot{x}_m - F_m) \end{aligned} \quad (1)$$

where \dot{x}_m and \dot{x}_s are the respective velocities of the master and the slave. F_h is the torque applied by the operator, and F_e is the torque applied externally on the remote system. F_m is the force reflected back to the master from the slave robot. F_s is the force information sent from the slave to master. \dot{x}_{sd} is the velocity derived from the scattering transformation at the slave side. The wave variables are defined by u and v .

The power, P_{in} , entering a system can be defined as the scalar product between the input vector x and the output vector y . Such a system is defined to be passive if and only if the following holds:

$$\int_0^t P_{in}(t) dt = \int_0^t x^T y d\tau \geq E_{store}(t) - E_{store}(0) \quad (2)$$

where $E(t)$ is the energy stored at time t and $E(0)$ is the initially stored energy. The power into the communication block at any time is given by

$$P_{in}(t) = \dot{x}_{md}(t)F_m(t) - \dot{x}_{sd}(t)F_s(t) \quad (3)$$

In the case of the constant communications delay where the time delay T is constant,

$$\begin{aligned} u_s(t) &= u_m(t-T) \\ v_m(t) &= v_s(t-T) \end{aligned} \quad (4)$$

Substituting these equations into (3), and assuming that the initial energy is zero, the total energy E stored in communications during the signal transmission between master and slave is found as

$$\begin{aligned} E &= \int_0^t P_{in}(\tau) d\tau = \int_0^t (\dot{x}_{md}(\tau)F_m(\tau) - \dot{x}_{sd}(\tau)F_s(\tau)) d\tau \\ &= \frac{1}{2} \int_0^t (u_m^T(\tau)u_m(\tau) - v_m^T(\tau)v_m(\tau) + v_s^T(\tau)v_s(\tau) - u_s^T(\tau)u_s(\tau)) d\tau \\ &= \frac{1}{2} \int_{t-T}^t (u_m^T(\tau)u_m(\tau) + v_s^T(\tau)v_s(\tau)) d\tau \geq 0 \end{aligned} \quad (5)$$

Therefore, the system is passive independent of the magnitude of the delay T . In other words, the time delay doesn't produce energy if the wave variable technique is used. Therefore, it guarantees stability for the time-delayed teleoperation.

For multi-DOF teleoperation systems, the inputs and outputs from the master and the slave are in vector form:

$$\underline{\dot{x}}_{sd} = \begin{bmatrix} \dot{x}_{sd} \\ \dot{y}_{sd} \\ \dot{z}_{sd} \end{bmatrix}; \underline{\dot{x}}_m = \begin{bmatrix} \dot{x}_m \\ \dot{y}_m \\ \dot{z}_m \end{bmatrix}; \underline{F}_s = \begin{bmatrix} F_s^x \\ F_s^y \\ F_s^z \end{bmatrix}; \underline{F}_m = \begin{bmatrix} F_m^x \\ F_m^y \\ F_m^z \end{bmatrix} \quad (6)$$

These inputs and outputs from the master and the slave sub-systems are transformed to wave variables using the B matrix for the multi-DOF case. For the simulations in this paper, the wave impedance matrix, B , is selected to be uncoupled as shown below:

$$B = \begin{bmatrix} b_x & 0 & 0 \\ 0 & b_y & 0 \\ 0 & 0 & b_z \end{bmatrix} \quad (7)$$

Munir and Book [2] write the wave transformation relation of equations in (1) in matrix notation to generalize it to multi-DOF systems as follows:

$$\begin{aligned} \underline{u}_s &= A_w \underline{\dot{x}}_{sd} + B_w \underline{F}_s \\ \underline{u}_m &= A_w \underline{\dot{x}}_m + B_w \underline{F}_m \\ \underline{v}_s &= C_w \underline{\dot{x}}_{sd} - D_w \underline{F}_s \\ \underline{v}_m &= C_w \underline{\dot{x}}_m - D_w \underline{F}_m \end{aligned} \quad (8)$$

where A_w , B_w , C_w , D_w , $B \in R^{n \times n}$ (are $n \times n$ matrices); \underline{u}_s , \underline{u}_m , \underline{v}_s , \underline{v}_m , $\underline{\dot{x}}_{sd}$, $\underline{\dot{x}}_m$, \underline{F}_s , $\underline{F}_m \in R^n$ (are $n \times 1$ vectors). A_w , B_w , C_w and D_w are the scaling matrices and n is the degree-of-freedom of the teleoperation system. In this paper, $n=3$ for the teleoperation system having three degrees of freedom.

Scaling matrices are determined using the impedance matrix (B), as follows:

$$A_w = \frac{\sqrt{2B}}{2}, \quad B_w = \frac{\sqrt{2B}}{2} (B^{-1}) \quad (9)$$

where usually C_w is selected to be the same as A_w , and D_w is selected to be the same as B_w .

MODIFICATION in WAVE VARIABLE METHOD for VARIABLE TIME-DELAYED TELEOPERATION

The block diagram below shows the modification described in the article ‘‘Bilateral Teleoperation over the Internet: the Time Varying Delay Problem’’ [6] for the wave variable method for the variable time-delayed teleoperation.

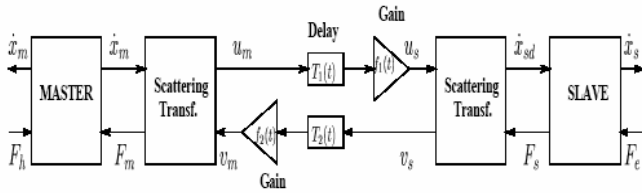


Figure 2. Modified scattering transformation for teleoperation with variable time delay

Time varying delay modifies the transmission equations to:

$$\begin{aligned} u_s(t) &= u_m(t - T_1(t)) \\ v_m(t) &= v_s(t - T_2(t)) \end{aligned} \quad (10)$$

where, $T_1(t)$ is the variable time delay in the path from the master to the slave and $T_2(t)$ is the variable time delay in the path from the slave to the master. It is assumed that in the article ‘‘Bilateral Teleoperation over the Internet: the Time Varying Delay Problem’’ [6]

$$\frac{dT_i}{d\tau} < 1; \quad i = 1, 2 \quad (11)$$

Substituting the modified transmission equations to the equation for the total energy stored in the communication line (5)

$$\begin{aligned} E &= \frac{1}{2} \left[\int_{t-T_1(t)}^t u_m^T(\tau) u_m(\tau) d\tau + \int_{t-T_2(t)}^t v_s^T(\tau) v_s(\tau) d\tau \right. \\ &\quad - \int_0^{t-T_1(t)} \frac{T_1'(\sigma)}{1-T_1'(\sigma)} u_m^T(\sigma) u_m(\sigma) d\sigma \\ &\quad \left. - \int_0^{t-T_2(t)} \frac{T_2'(\sigma)}{1-T_2'(\sigma)} v_s^T(\sigma) v_s(\sigma) d\sigma \right] \end{aligned} \quad (12)$$

where $\sigma = \tau - T_i(\tau) = g_i(\tau)$ and $T_i'(\sigma) = \frac{dT_i}{d\tau} \Big|_{\tau=g_i^{-1}(\sigma)}$.

The last two terms in the total energy stored equation show that passivity can not be guaranteed for variable time-delayed teleoperation. In the modified wave variable method scheme in Figure 2, a time varying gain f_i is inserted after the time varying delay block. Therefore the new transmission equation become

$$\begin{aligned} u_s(t) &= f_1(t) u_m(t - T_1(t)) \\ v_m(t) &= f_2(t) v_s(t - T_2(t)) \end{aligned} \quad (13)$$

The total energy stored can be re-written using the new transmission equations as

$$\begin{aligned} E &= \frac{1}{2} \left[\int_{t-T_1(t)}^t u_m^T(\tau) u_m(\tau) d\tau + \int_{t-T_2(t)}^t v_s^T(\tau) v_s(\tau) d\tau \right. \\ &\quad - \int_0^{t-T_1(t)} \frac{1-T_1'(\sigma) - f_1^2}{1-T_1'(\sigma)} u_m^T(\sigma) u_m(\sigma) d\sigma \\ &\quad \left. - \int_0^{t-T_2(t)} \frac{1-T_2'(\sigma) - f_2^2}{1-T_2'(\sigma)} v_s^T(\sigma) v_s(\sigma) d\sigma \right] \end{aligned} \quad (14)$$

If f_i is selected that $f_i^2 = 1 - T_i'$ for the total energy stored equation, the last two terms of the equation are eliminated and it can be said that the system is passive. In fact, in the article ‘‘Bilateral Teleoperation over the Internet: the Time Varying Delay Problem’’ [6] it is said that the variable time-delayed system is considered to be passive if f_i satisfies

$$f_i^2 \leq 1 - \frac{dT_i}{dt}; \quad i = 1, 2 \quad (15)$$

The change in the variable gain due to the variable time delay is computed using the relation described in the plot below [6].

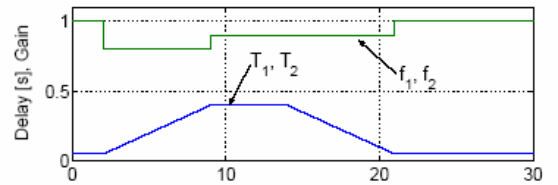


Figure 3. Change of the variable gain due to the change in time delay

This variable gain can be called an adaptive gain that adapts itself with respect to the change in time delay.

DEVELOPMENT of the 3-DEGREE-of-FREEDOM (DOF) TELEOPERATION SYSTEM MODEL in MATLAB®

The teleoperation system has two sub-systems: The master controller, which is modeled as a three-DOF joystick, and the slave robot, which is a three-DOF Cartesian robot. Cartesian robot is a manipulator with three prismatic joints which each of them are aligned









with an axes of the Cartesian coordinates. The joystick is modeled to be uncoupled in terms of its three degrees of freedom since this is the case for the actual joystick to be built for the real-time application of this work at the FIU Robotics and Automation Laboratory in Miami, Florida. The two sub-systems are modeled in Matlab[®] using the Simmechanics blocks of Simulink. The Simmechanics blocks of Matlab[®] Simulink are listed in Table 1, and the two modeled sub-systems are depicted in Figures 4 and 5.

Torque inputs applied by the operator on the joystick, denoted by “Joy_Out” in the block diagram (Figure 4), are fed into the joint actuators of the joystick with the force feedback information from the slave robot and the joystick spring dynamics output, “Torque of Spring.” The “Spring&Damper” blocks are used to model a spring system to move the joystick to the null position when there is no other torque applied to it. The “Spring & Damper” block is composed of simple Simulink blocks that multiply the position and velocity feedback with certain gains to make the block act as a spring-damper system. Force feedback information from the slave is either sent (1) while there is a time delay by “Slave_FF” or (2) while there is no time delay by “Force_FB”, which is switched by the “Time_Dly” switch input generated from the main window. The rest of the blocks of Figure 4 are the blocks from Simmechanics library of Simulink to model the kinematics and dynamics of the joystick. The Simmechanics blocks that are used to develop the master and the slave robot are introduced below.

Figure 5 shows the Simulink window of the slave robot modeled. The kinematics and dynamics of the robot are also modeled with the Simmechanics library of Simulink. Different than the master, the slave has three prismatic joints, which enables it to work like a Cartesian robot with three-DOF. The slave robot takes the velocity command from the master, “Slave_V_W”. If there is a time delay or it is switched to take the velocity command from the master output directly, “Pos_FB”, by the help of the “Time_Dly” switch and compares it with its velocity feedback “Slave_V” to feed the necessary information to the PD controller. Also, it sends the necessary output to create the force information in relation to the proximity to the constraints, by comparing the position information in three-DOF, “Slave_P”.

Figure 6 shows the communications protocol between the master and the slave. There are four switching conditions to enable usage of the wave variable technique for the time-delayed teleoperation. These switches are operated by the input “Wave_Vrb” generated from the main window. The rest of the blocks of the “Communication Line” block are to construct the wave variable method into the communication line between the master and the slave. The amount of time delay is set from the “Time Delay” blocks. Also in this block there is a switching between the constant time delay to the variable time delay, which is operated by the switch “Varying Time Delay On/Off” in the main interface window in Figure 7. The switching from the wave variable technique to the modified one is done in the “Vr/no Gain” blocks by enabling or disabling the adaptive gain, which is operated by the switch “Variable Gain on/Off” in the main interface window in Figure 7. All the calculations made in the communications line block are matrix based. The lines between the blocks carry information for three-DOF in vector format.

Table 1. Description of the Simmechanics blocks

	“Ground” block grounds one side of a joint block to a fixed location in the World coordinate system
	“Joint Initial Condition” block sets the initial linear/angular position and velocity of some or all of the primitives in a joint block.
	“Joint Actuator” block actuates a joint block primitive with generalized force/torque or linear/angular position, velocity, and acceleration motion signals.
	“Joint Sensor” block measures linear/angular position, velocity, acceleration, computed force/torque and/or reaction force/torque of a joint primitive.
	“Revolute” joint block represents one rotational degree of freedom. It can be driven by the “Joint Actuator” block and its motion can be measured by the “Joint Sensor” block if the blocks are attached to this block.
	“Prismatic” joint block represents one translational degree of freedom. It can be driven by the “Joint Actuator” block and its motion can be measured by the “Joint Sensor” block if the blocks are attached to this block.
	“Body” block represents a user-defined rigid body. “Body” block is defined by mass, inertia tensor and coordinate origins.
	“Body Sensor” block measures linear/angular position, velocity, and/or acceleration of a “Body” block with respect to a specified coordinate system.

The main control window of teleoperation is shown in Figure 7. The subsystems are marked with “Master (Joystick)” and “Slave.” The generation of time delay and the application of the wave variable technique to the communications line are in the “Communication Line” block of the main control window. The conversion of information to matrix and vector format is accomplished in a block named “Matrix conversions.” The force information from the position of the slave is also created from this subsystem. The operator’s interaction to apply torque to the joystick is incorporated through the joystick torque inputs “Joy_Out_1”, “Joy_Out_2,” and “Joy_Out_3” representing the y, x and z axes, respectively.

The motion of the slave robot (Cartesian robot) is observed from the scope in the “Slave” subsystem. There are also four switches that appear on the main control window of the teleoperation. The first one with a tag “Time Delay On/Off” is to enable the time delay on the communications line of the system. This switch generates an input, “Time_Dly”, to switch the time delay “on” or “off” in the master and the slave robot. The second switch with a tag “Wave Variables On/Off” enables application of the wave variable technique to the system with a constant time delay. This switch also generates an input called “Wave_Vrb” to accomplish the necessary switch in the “Communication Line” block. The third switch is to enable the variable time delay, which is denoted by “Varying Time Delay On/Off”. The output from this switch changes the behavior of the delay from constant to varying. The fourth and the last switch enables the adaptive gain in the communication line to switch from the wave variable technique to the modified one. This switch is denoted by “Varying Gain On/Off” in Figure 7.

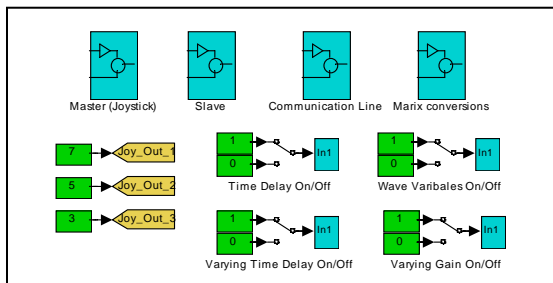


Figure 7. Main teleoperation interface window

SIMULATION RESULTS FOR CONSTANT TIME-DELAYED TELEOPERATION

The first set of simulations is carried out for time delays of 0.1, 0.2 and 0.5 second and in the absence of the wave variable technique. This set of simulations will provide information on how the time delay plays a role in the stability of teleoperation and how oscillary motion increases with increasing time delays. The second set of simulations is carried out for time delays of 0.1, 0.2

and 0.5 second in the presence of wave variables to improve stability in teleoperation [7].

The scenario for these simulations assumes that the operator applies constant but differing amounts of torques to each of the three degrees of freedom of the joystick to send a constant velocity command vector to the slave (remote Cartesian robot). The slave robot’s proximity sensors are set to 50 inches for the x-axis, 30 inches for the y-axis and 70 inches for the z-axis. Therefore, as it goes beyond the limits, the slave robot sends force information in vector format to the master with magnitude proportional to the distance violated beyond the limits. During all this time, the operator still exerts constant amounts of torque to the joystick to make the slave robot move in the same direction. This type of operation is likely to cause an oscillatory motion about the constraint, which should be damped to a position just above the 50-meter limit due to the steady input torque provided by the operator.

Figures 8, 9, and 10 are presented to illustrate the effect of increasing time delays on the stability and oscillations of the manipulation. Slave motion oscillates about different limits for each degree of freedom, as it was set. It is noted that the magnitude of oscillations increases, as does the time delay.

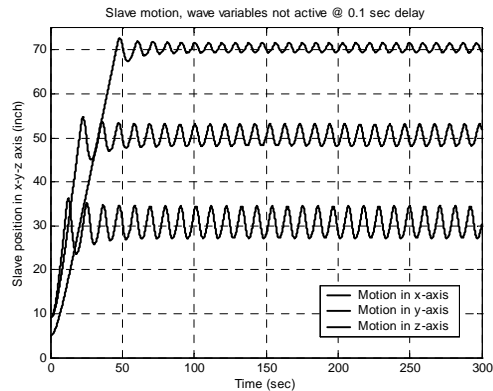


Figure 8. Effect of 0.1 second time delay on 3-DOF teleoperation

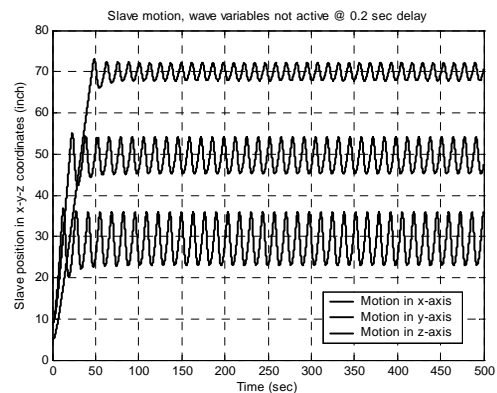


Figure 9. Effect of 0.2 second time delay on 3-DOF teleoperation

It can be observed from the figures that when the wave variable technique is not activated the slave motion oscillates without any damping. The following figures 11, 12, and 13 are presented to highlight the effect of the wave

variables on the same system that was unstable under time delays of 0.1, 0.2, and 0.5 second, respectively.

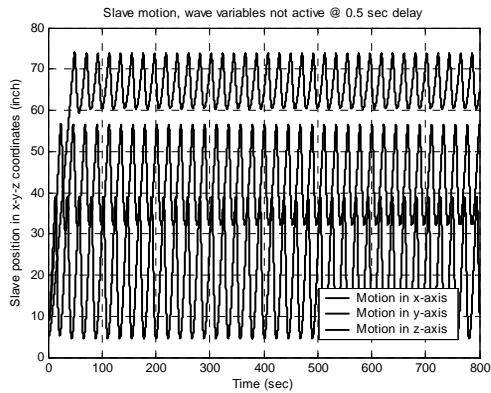


Figure 10. Effect of 0.5 second time delay on 3-DOF teleoperation

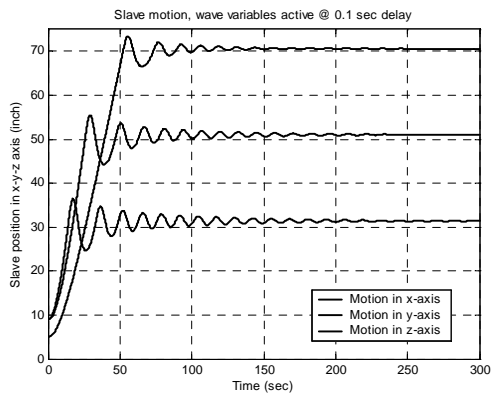


Figure 11. Effect of wave variable technique on a 0.1 second time-delayed 3-DOF teleoperation

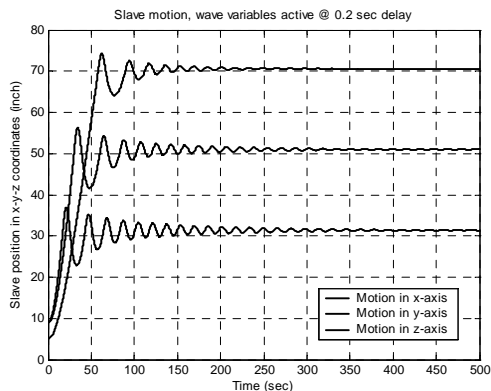


Figure 12. Effect of wave variable technique on a 0.2 second time-delayed 3-DOF teleoperation

When the wave variable technique is activated, the motion of the slave is dampened, and converged to a point just above the limiting value of 50, 30, 70 inches for x, y and z axes, respectively. In general, larger settling times are observed when higher time delays are modeled in communication lines. For example, the 0.1 second time-delayed teleoperation settles in about 300 milliseconds where it is about 500 milliseconds for 0.2 second time-delay, and 800 milliseconds for 0.5

second time-delay; all for the same wave impedance.

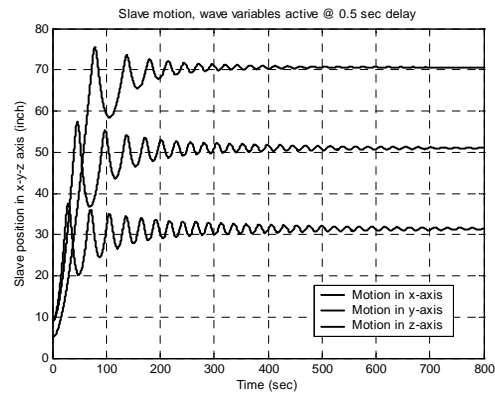


Figure 13. Effect of wave variable technique on a 0.5 second time-delayed 3-DOF teleoperation

SIMULATION RESULTS FOR VARIABLE TIME-DELAYED TELEOPERATION

The task defined for the constant time-delayed teleoperation is also used for the variable time-delayed teleoperation simulations. Figure 14 shows the case when there is variable time delay in the system and no wave variables control over it. Time delay in the communication line of the system changes from 0.5 seconds delay to 0.1 seconds delay in the fashion of the plot for variable time delay in Figure 3.

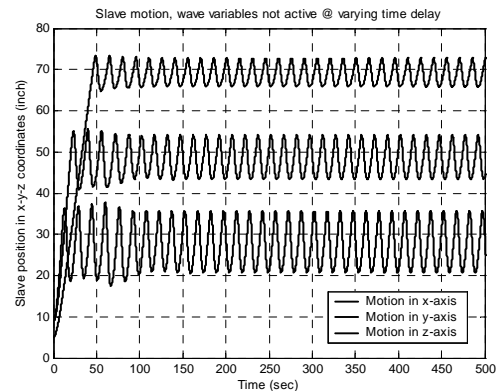


Figure 14. Effect of variable time delay on 3-DOF teleoperation

Figure 15 shows the case when there is variable time delay and the wave variable technique is applied. It can be observed from the figure that the system is still unstable under the influence of the wave variables for the variable time delay but the oscillations are damped with respect to the case where the wave variable technique is not applied.

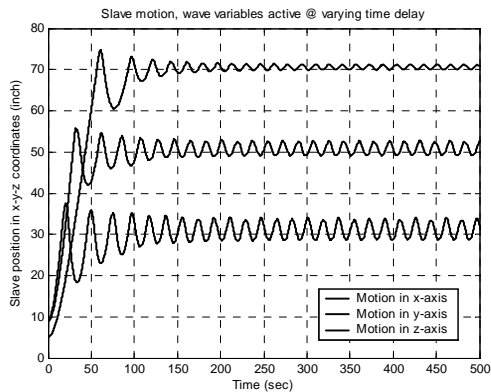


Figure 15. Effect of wave variable technique on the variable time-delayed 3-DOF teleoperation

Figure 16 shows the case when the modified wave variable technique is applied to the system with variable time delay. As shown in the figure, the adaptive gain placed just after the time delay in the communication lines as explained in Modification in Wave Variable Section guaranteed the stability for the variable time delay case.

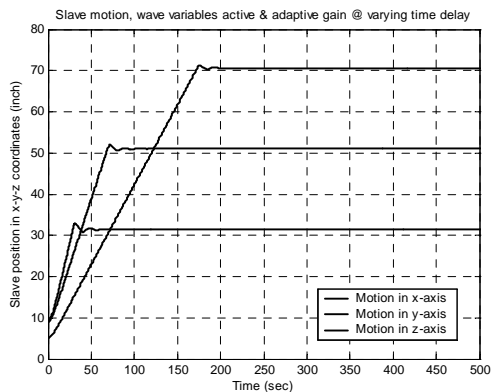


Figure 16. Effect of modified wave variable technique on the variable time-delayed 3-DOF teleoperation

CONCLUSIONS

In this article, the theory of wave variable technique, modeling of 3-DOF teleoperation system using Matlab[®], and the simulation results of this teleoperation system with different tasks are presented. Although the main task remains the same for each simulation, changing the time delay and activating and deactivating the wave variables in simulations provided a better understanding of the necessity of the wave variables in constant time delayed teleoperation.

Currently we are working on a real-time application of the simulations that are presented in this paper. The long-term goal is to implement the developed modeling and simulations package to control remote systems over long distances in real-time via Internet and assess the commercial value of the proposed approach.

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