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A Study on Multiple Degree-of-Freedom Force Reflecting Teleoperation

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Abstract

This article reviews the wave variable method as it applies to multi degree-of-freedom teleoperation systems. To demonstrate the effect of wave variables on the stability of a time-delayed multi-degree-of-freedom system, initial simulation results on a three-axis robot 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.

1. Introduction and background

Teleoperation has attracted interest in researchers partly because it is utilized in a wide variety of applications that span the space, nuclear reactors, battlefields, security needs, undersea tasks, medical operations, and training, among others. Often teleoperation has been associated with the time delay problem when it is implemented over longer distances (when controlling a device on Mars, for instance), or when it utilizes the internet infrastructure to communicate with a remote system. The system and its control become more complicated when force reflection is introduced. Such a system used under significant time delays poses a challenging control design problem since even the stability of such a system cannot be easily guaranteed.

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.

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. Section 3 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 Section 4. 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. Lastly, conclusions and planned future work appear in Section 5.

2. The wave variable method

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].

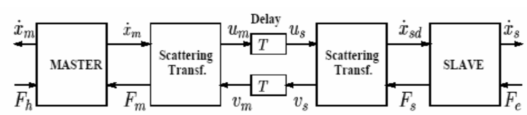


Figure 1. Scattering transformation for teleoperation with time delay

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

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

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's.

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:

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

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

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

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

$$u_s(t) = u_m(t-T)$$
$$v_m(t) = v_s(t-T) \qquad (4)$$

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

$$E = \int_0^t P_{in}(\tau)d\tau = \int_0^t (\dot{x}_{md}(\tau)F_m(\tau) - \dot{x}_{sd}(\tau)F_s(\tau))d\tau$$

$$= \frac{1}{2}\int_0^t (u_m^T(\tau)u_m(\tau) - v_m^T(\tau)v_m(\tau) + v_s^T(\tau)v_s(\tau) - u_s^T(\tau)u_s(\tau))d\tau$$

$$= \frac{1}{2}\int_{t-T}^t (u_m^T(\tau)u_m(\tau) + v_s^T(\tau)v_s(\tau))d\tau \geq 0 \qquad (5)$$

and, 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:

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

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:

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

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

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

where A_w, B_w, C_w, D_w, $B \in R^{nxn}$; $\underline{u}_s$, $\underline{u}_m$, $\underline{v}_s$, $\underline{v}_m$, $\underline{\dot{x}}_{sd}$, $\underline{\dot{x}}_m$, $\underline{F}_s$, $\underline{F}_m \in R^n$. 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:

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

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.

3. Development of the 3-degree-of-freedom (DOF) teleoperation system model in Matlab©

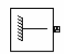
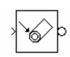
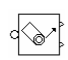
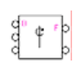
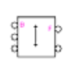
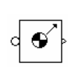
The teleoperation system has two sub-systems: The master controller, which is modeled as a three-DOF joystick, and the slave robot, which is a three-DOF Cartesian robot. The joystick is modeled to be uncoupled in terms of its three degrees of freedom since this is the case for the actual joystick to 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 2 and 3.

Torque inputs applied by the operator on the joystick, denoted by "Joy_Out" in the block diagram (Figure 2), 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. It 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 2 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 3 shows the Simulink window of the slave robot modeled. The kinematics and dynamics of the robot is 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 4 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. 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.

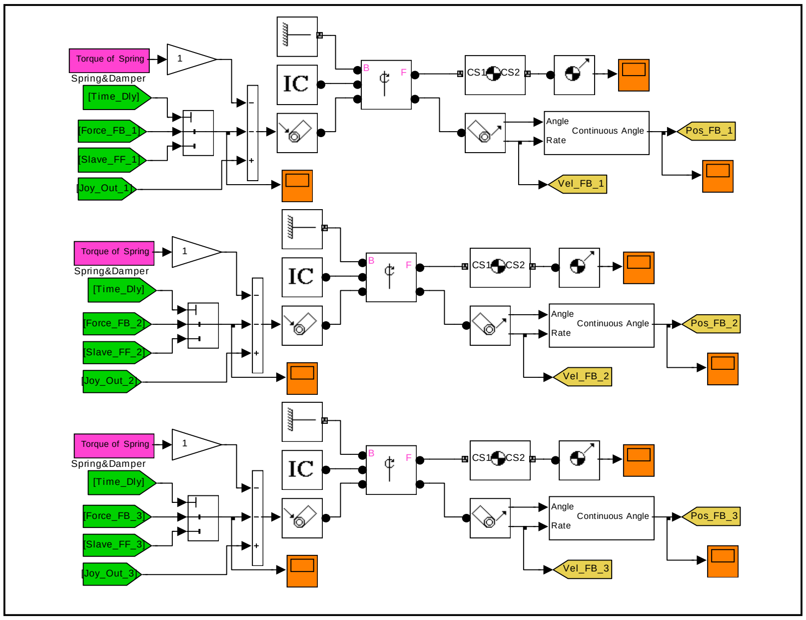


Figure 2. Master (joystick) sub-system window

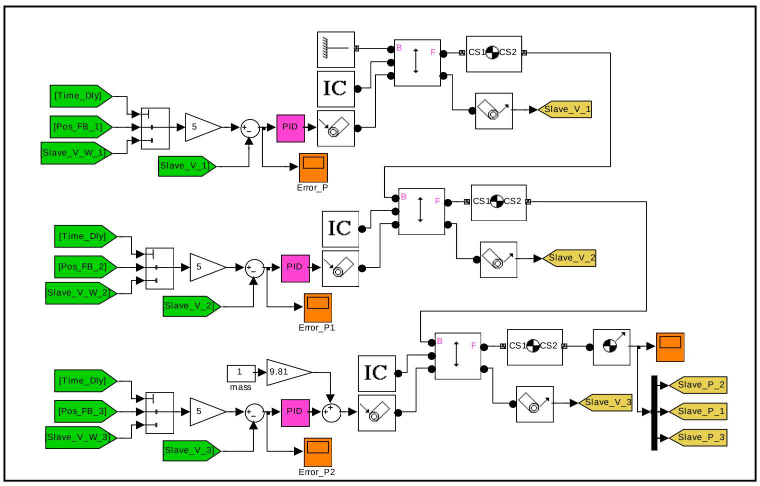


Figure 3. Slave sub-system window

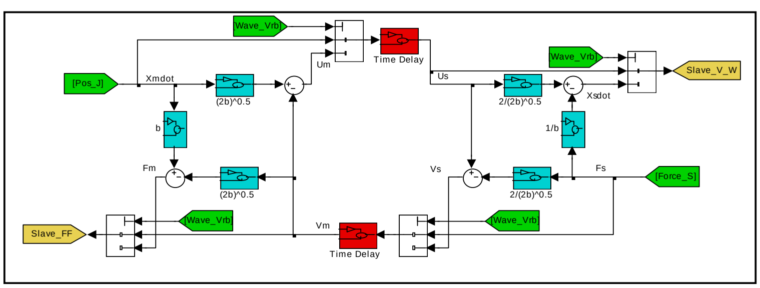


Figure 4. Communication line block window

The main control window of teleoperation is shown in Figure 5. 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 two 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.

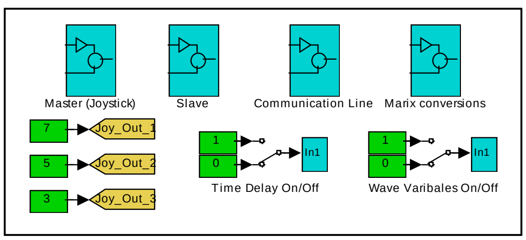


Figure 5. Main teleoperation interface window

4. Teleoperation simulation results

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.

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 in for the x-axis, 30 in for the y-axis and 70 in 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 6, 7, and 8 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.

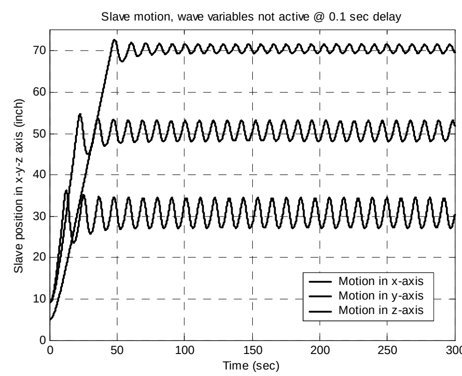


Figure 6. Effect of 0.1 second time delay on 3-DOF teleoperation

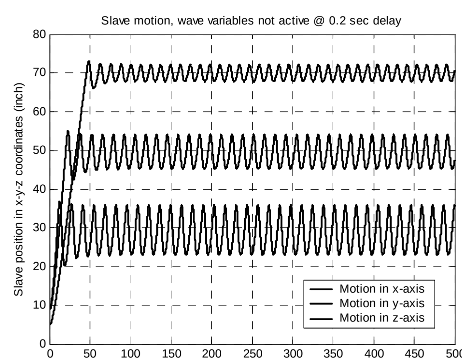


Figure 7. Effect of 0.2 second time delay on 3-DOF teleoperation

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 9, 10, and 11 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 0.3 second, respectively.

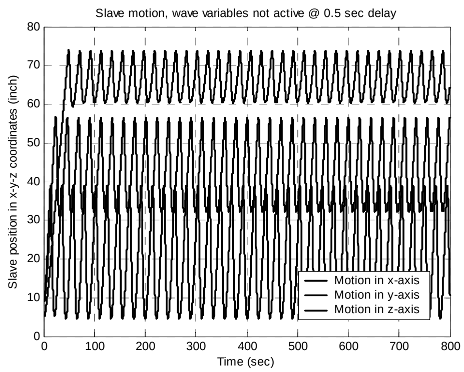


Figure 8. Effect of 0.5 second time delay on 3-DOF teleoperation

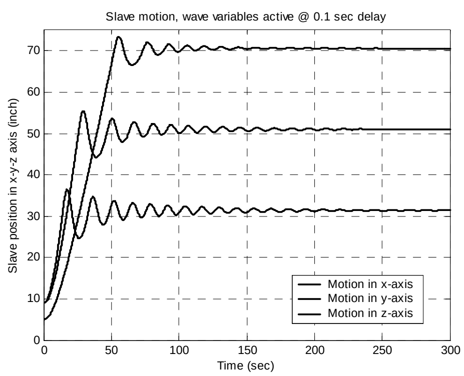


Figure 9. Effect of wave variable technique on a 0.1 second time-delayed 3-DOF teleoperation

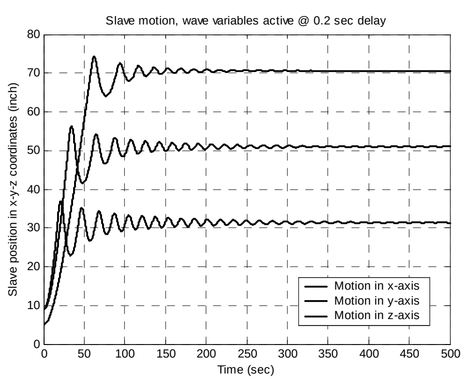


Figure 10. Effect of wave variable technique on a 0.2 second time-delayed 3-DOF teleoperation

As the wave variable technique 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 instance, 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.

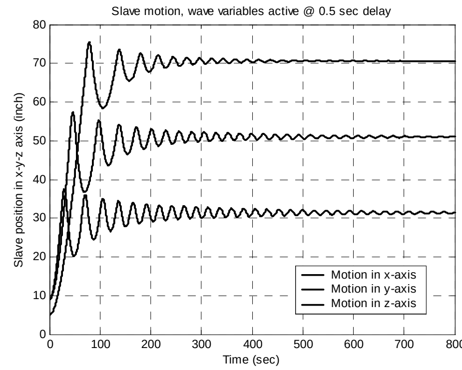


Figure 11. Effect of wave variable technique on a 0.5 second time-delayed 3-DOF teleoperation

5. Conclusions

A Matlab©-based system model is developed for multi-DOF teleoperation systems, and initial simulation results are presented by using the wave variable technique to control a 3-DOF teleoperation system. Initial results show that the Matlab© model provides a robust modeling and simulations environment, and that the wave variable technique indeed provides stability to an unstable system when time delays are introduced. More in-depth study of the method and the effect of scaling matrices in terms of the practical implementation of the method are under investigation. The long-term goal is to implement the developed modeling and simulations package to control remote systems over long distances in real-time and assess the commercial value of the proposed approach.

6. References

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