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Effects of Time Delay on Force-Feedback Teleoperation Systems

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Abstract

This paper focuses on the effects of constant time-delays on force-reflecting teleoperation systems. The wave variable method is used to investigate its effectiveness in the presence of time delays. The master (joystick) and the slave system (remote mobile robot) dynamics and the controller are modeled in the Matlab© environment. Performance of the teleoperation system controlled by the wave variable technique is simulated under the effect of time delays and compared to that of the system without time delay and when the wave variable method is not applied. It is noted that the development of the simulation model in Matlab© aims to widen the current research to real-time application of the same control algorithm by using the Matlab© Real-Time Windows Target.

1. Introduction

Teloperation systems have been popular for decades especially for hazardous and unstructured tasks. Such tasks include nuclear reactors, space applications, military uses, medical operations and deep-sea explorations to name a few [5]. More recently, explorations on Mars have renewed the interest in this topic.

Teleoperation describes two systems that are distant from each other and coupled in a way that both send and receive commands from each other. The information sent from the master to the slave controller is the position and/or velocity command and the information sent from the slave to the master is usually the force command. The force feedback from the slave provides valuable information to the master to get the feeling of the conditions the slave faces in order to improve the operator's ability to perform the manipulation with small errors, which could save the slave from exerting unnecessary amounts of force on the environment.

The time-delay between the master controller and the slave robot on the communication lines has arisen as a dominant factor of instability in teleoperation. To overcome this defect, Anderson and Spong in 1989 introduced the wave variable technique [1], which is further studied by Niemeyer and Slotine [2], [3]. Niemeyer also researched this technique on time-delayed force reflecting teleoperation systems in his dissertation [4]. This technique simply focuses on how to make the energy created as a result of the time delay zero in order to guarantee passivity, which will result in a robust system if subjected to constant time delays.

The wave variable technique is further discussed in this paper, and initial simulations are presented. The aim in the present work is to gain insight in this method and implement it to a prototype force-reflecting system to evaluate its effectiveness for possible commercial use.

The first simulation for teleoperation is carried out for the system with no time delays to observe the best performance that it yields for the coupled master and slave systems. The next step is the introduction of a time delay without any compensation or a technique to guarantee stability to see how the system performance and stability is affected. Normally, a deterioration of the system response is expected.

Finally, as a concluding simulation, the wave variable technique is applied to the teleoperation system in the presence of time delays. Utilizing the results of the simulation, the necessity of the wave variable technique and the improvement it makes on the performance of the system are discussed in the conclusion section of this paper. The following section describes the wave variable technique and subsequently the development of the teleoperation system model in the Matlab© environment.

2. Wave variable technique

The wave variable technique is simply presented in the sketch below showing the transformation of the velocity and force feedback information to the wave variables as the scattering transformation.

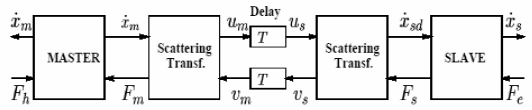


Figure 1. Scattering transformation for teleoperation with time delay

The transformation using the notation in [2] is defined as follows:

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

where $\dot{x}_m$ and $\dot{x}_s$ are the respective velocities of the master and the slave. F_h is the operator torque and F_e is the environment torque. 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 scattering transformation at the slave side. u and v's are the wave variables.

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 as passive if and only if

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

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

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

In case of the constant communication delay where *T* is constant,

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

Substituting these equations into (3), and assuming that the initial energy is zero, it is computed that the total energy stored in the communications during the signal transmission between master and slave is given by

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

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

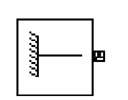
$$= \frac{1}{2}\int_{t-T}^t (u_m^T(\tau)u_m(\tau) + v_s^T(\tau)v_s(\tau))d\tau \ge 0 \tag{5}$$

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, and; therefore, guarantees stability for the time-delayed teleoperation.

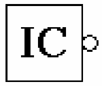
3. Development of the teleoperation system model in Matlab©

The teleoperation system mainly has two sub-systems: The master controller, which is, in this case, a one-degree-of-freedom (DOF) joystick, and the slave robot, which is modeled as a one-DOF slider. These two sub-systems are modeled in Matlab© using the Simmechanics blocks of Simulink. The sub-systems are shown in Figures 2 and 3 below.

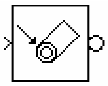
The torque input applied by the operator on the joystick, denoted by "Joy_Out" in the block diagram (Figure 2), is fed into the joint actuator of the joystick with the force feedback information from the slave robot and the joystick spring dynamics output, "Torque of Spring". The "Spring&Damper" block is 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 while there is a time delay by “Slave_FF” or 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 defined below.



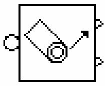
“Ground” block, grounds one side of a joint block to a fixed location in the World coordinate system



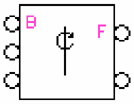
“Joint Initial Condition” block, sets the initial linear/angular position and velocity of some or all of the primitives in a joint block.



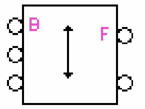
“Joint Actuator” block, actuates a joint block primitive with generalized force/torque or linear/angular position, velocity, and acceleration motion signals.



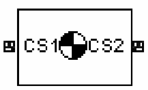
“Joint Sensor” block, measures linear/angular position, velocity, acceleration, computed force/torque and/or reaction force/torque of a joint primitive.



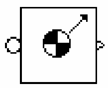
“Revolute” joint block, represents one rotational degree of freedom. It can be driven by the “Joint Actuator” block and its motion can be measured by the “Joint Sensor” block if the blocks are attached to this block.



“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.

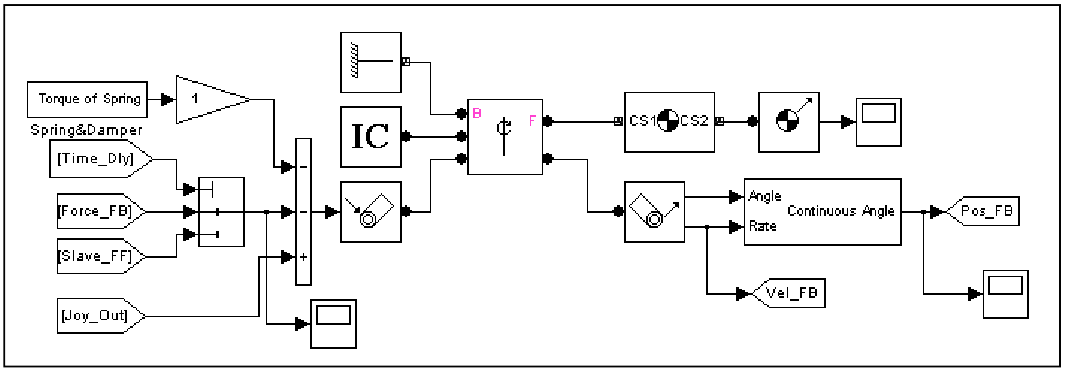


Figure 2. Master (joystick) sub-system window

Figure 3 shows the Simulink window of the modeled slave robot. The kinematics and dynamics of the robot is also modeled with the Simmechanics library of Simulink. Different than the master, the slave has one prismatic joint, which enables it to work like a slider mechanism with one degree of freedom. The slave robot simply 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 means of proximity to the modeled wall, by the position of itself “Slave_P”.

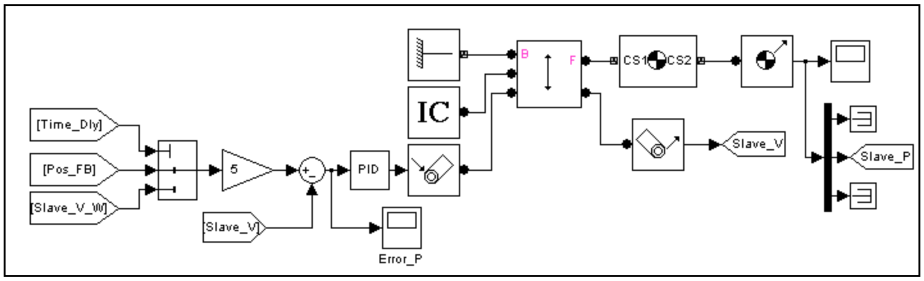


Figure 3. Slave sub-system window

Figure 4 shows the communication between the master and the slave. Force feedback information is created with the “FF Command” in Figure 4. “FF activation” block senses the contact of the slave robot to the environment and enables the force feedback information to be sent to the master by switching from zero input block to “FF Command” block. There are four other 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.

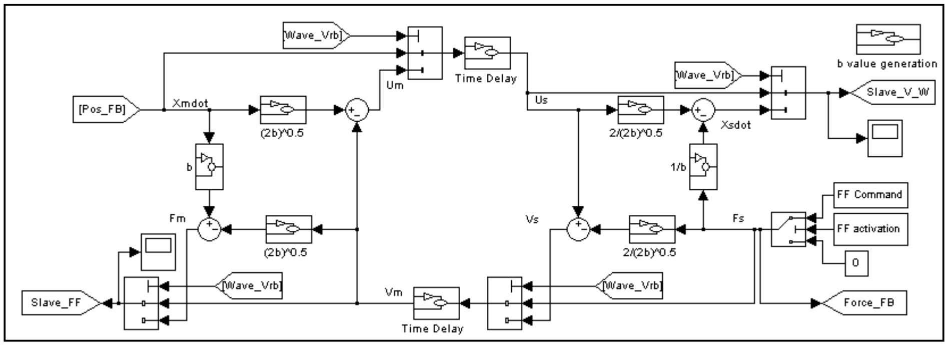


Figure 4. Communication line block window

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 communication line are in the “Communication Line” block of the main control window. The operator’s interaction to apply torque to the joystick is accomplished through the joystick with the tag “Operator Torque Input”. The motion of the master robot (joystick) under the influence of the torque input from the operator and the force feedback provided from the slave robot is observed from the joystick with the tag “Actual Joystick Motion.”

The motion of the slave robot (slider) is observed from the slider on the main control window with the tag “Slider Motion”. There are also two switches that appear on the main control window of teleoperation. The first one with the tag “Time Delay On/Off” is to enable the time delay on the communication line of the system. This switch generates an input, “Time_Dly”, for the switching in the master and the slave robot. The second switch with the tag “Wave Variables On/Off” enables to apply wave variable technique to the system with the constant time delay. This switch also generates an input, “Wave_Vrb”, for the switching in the “Communication Line” block.

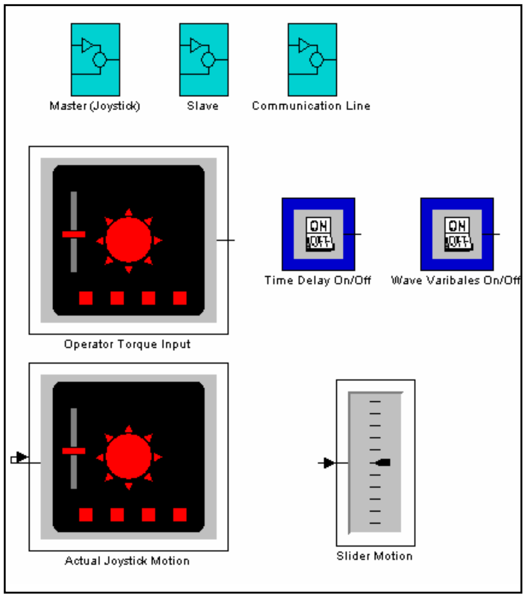


Figure 5. Main teleoperation interface window

4. Teleoperation simulation results

The first simulation carried out in this study models a communications line with no time delay. This simulation gives an idea of the ideal case where the two sub-systems are coupled perfectly without any delays. The second set of simulations is carried out for time delays of 0.1, 0.2 and 0.5 second and in the absence of wave variable technique. This set of simulations provides information on how time delays play a role in the stability of teleoperation. Finally, the last 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 demonstrate stability in teleoperation.

The task for each simulation is set as follows: The operator applies a steady torque to the master controller (joystick) to send a constant velocity command to the slave. The slave sliders proximity sensor is set to 50 inches. Therefore, as it reaches beyond the set value of 50 inches, the slave slider sends force information to the master with respect to the distance violated beyond the limit. During all this time, operator still exerts the constant torque to the joystick to make the slave slider 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 limiting value of 50 inches due to the steady operator torque input.

Figures 6, 7, and 8 are presented to demonstrate the effect of wave variable technique on the stability of teleoperation. The solid lines on the plots represent the slave motion in the absence of wave variable technique for the communication between the master and the slave. The dashed line shows the slave response in the presence of wave variables. It can be observed from the figures that when the wave variable technique is not activated, the slave motion oscillates without any damping to converge the motion to a steady state. As the wave variable technique is activated, the motion of the slave is dampened and therefore it converges to a point just above the limiting value of 50 inches.

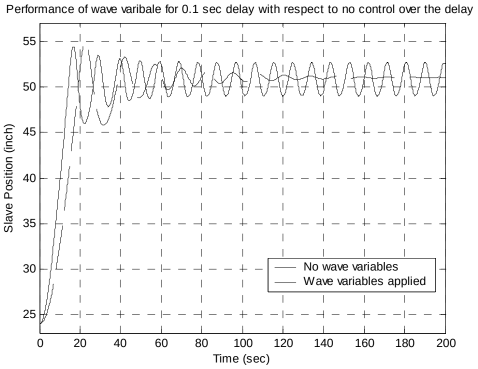


Figure 6. Effect of wave variable technique on a 0.1 second time-delayed teleoperation

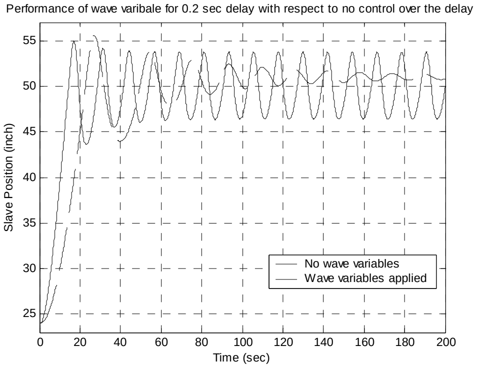


Figure 7. Effect of wave variable technique on a 0.2 second time-delayed teleoperation

While guaranteeing the stability of the teleoperation with a constant time delay, the decrease in the manipulation speed caused by the application of wave variable technique can be observed from the three figures above. Figure 9 illustrates a different collection of system responses ranging from no time delay to 0.1, 0.2 and 0.5 second of time delays.

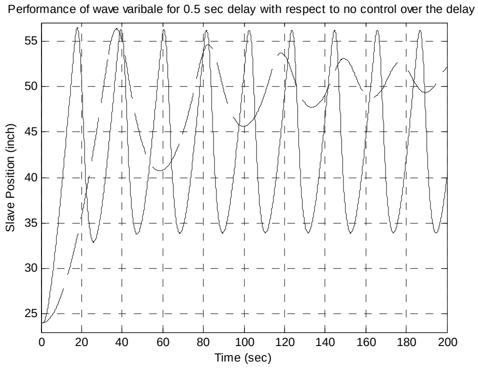


Figure 8. Effect of wave variable technique on a 0.5 second time-delayed teleoperation

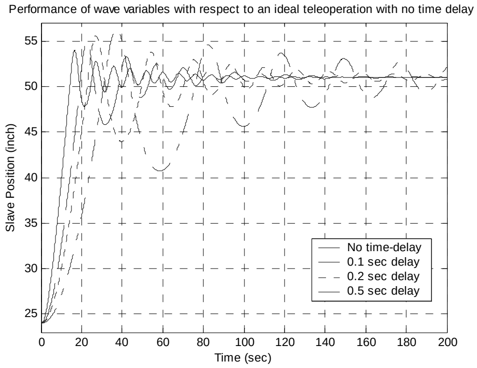


Figure 9. Side effects of wave variables with regard to the ideal teleoperation with no time delay

It is observed from Figure 9 that as the time delay increases, the magnitude of overshoot increases but the manipulation speed decreases. Also an increase of time delay results in an increase in the time required to settle the slave slider.

5. Conclusions

In this paper, the theory of wave variable technique, modeling of a teleoperation system, 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.

As the wave variable technique enhances the stability of constant time delayed teleoperation, it is observed that the drawbacks of the wave variables are stated as an increase in the magnitude of the overshoot as the system response reaches the set point and the general decrease in manipulation speed. The decrease in manipulation speed and increase in the overshoot can be observed more clearly as the time delay increases.

The next step for the continuing study of wave variables will be the investigation of the effect of the wave impedance, *b*, on teleoperation performance. The controller developed in Matlab© for this work will also be directly used in real-time control of a prototype teleoperation system, and simulation results presented here will be compared to the experimental results to further evaluate the validity and effectiveness of the modeling technique as well as the wave variable method to assess its use in practical teleoperation applications.

6. References

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