Modeling of a Single DOF Force Feedback Teleoperation System

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Abstract

The objective of this paper is to describe the modeling of a single degree-of-freedom (DOF) teleoperation system by using the Matlab© software tool. Modeling a teleoperation system consists of the modeling of the dynamics and kinematics of two subsystems as well as the communication line between them to couple the systems and user interface to interact with the system. The subsystems of a teleoperation system are the master and the slave. In this paper, subsystems are chosen to have a single degree-of-freedom.

A constant time-delay is also modeled to see the effect of time delays on the stability of teleoperation. The wave variable technique is then introduced to enhance the stability of the system. Preliminary simulation results are also presented in an effort to demonstrate the use of the developed model.

Introduction

Hazardous and unstructured tasks found in nuclear reactors, space applications, military uses, medical operations and deep-sea explorations often employ teleoperated systems. More recently, space explorations such as the Space Station development efforts and missions to Mars have renewed the interest in this area.

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 receive the feeling of the conditions the slave faces in order to improve the operator's ability to perform the manipulation with small or no errors, which could save the slave from exerting unnecessary amounts of force to the environment.

The time delay between the master controller and the slave robot has been seen as a dominant factor of instability in teleoperation. In order to overcome this problem, Anderson and Spong in 1989 [1] introduced the wave variable technique, which is further studied by Niemeyer and Slotine [2], [3]. Niemeyer also studied 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 method is further discussed in the next section.

The modeling of the subsystems of the teleoperated system is described in the third section. Also the modeling of communication line between the subsystems and the user interface is illustrated in this section.

Preliminary results of the developed teleoperation simulation are presented in the fourth section for different simulation tasks. The first simulation for teleoperation is carried out for the system having no time delay to observe the best performance that it can have for the coupled master and slave systems. In the second simulation, time delay is introduced without any compensation or a technique to guarantee stability to see how the system performance and stability is affected. In the third simulation, the wave variable technique is applied to the teleoperated system in the presence of time delays. Finally different wave impedance terms are examined for the same simulation. Utilizing preliminary simulation results of the simulations, the necessity of the wave variable method and the

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improvement it makes on the performance of the system are discussed in the conclusion section of this paper.

Wave variable technique

The block diagram below summarizes the wave variable method in a straightforward manner. The scattering transformation defines the transformation of the velocity and force feedback information to the wave variables.

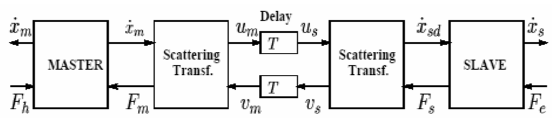


Figure 1. Scattering transformation for teleoperation with time delay

By using the notation developed in [2], the scattering transformation is described as follows:

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

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 is defined as the scalar product between the input vector x and the output vector y. Such a system is said to be passive if and only if

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

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 described 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 a 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

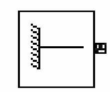
$$
\begin{aligned}
E &= \int_0^t P_{in}(\tau)d\tau = \int_0^t (\dot{x}_{md}(\tau)F_m(\tau) - \dot{x}_{sd}(\tau)F_s(\tau))d\tau \\
&= \frac{1}{2}\int_0^t (u_m^2(\tau) - v_m^2(\tau) + v_s^2(\tau) - u_s^2(\tau))d\tau \\
&= \frac{1}{2}\int_{t-T}^t (u_m^2(\tau) + v_s^2(\tau))d\tau \geq 0
\end{aligned} \tag{5}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

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. Therefore, it guarantees stability for the time-delayed teleoperation.

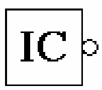
Development of the teleoperated system model in Matlab©

The teleoperated system mainly has two sub-systems: The master controller, which is a one-DOF joystick, and the slave robot, which is also 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.

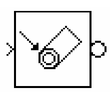
The torque input applied by the operator on the joystick, denoted by "Joy_Out" in the block diagram (Figure 2), is fed into the joint actuator of the joystick with the force feedback information from the slave robot and the joystick spring dynamics output, "Torque of Spring". The "Spring&Damper" block 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 is 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 briefly introduced below.



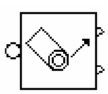
: "Ground" block grounds one side of a joint block to a fixed location in the World coordinate system.



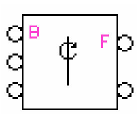
: "Joint Initial Condition" block sets the initial linear/angular position and velocity of some or all of the primitives in a joint block.



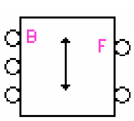
: "Joint Actuator" block actuates a joint block primitive with the generalized force/torque or linear/angular position, velocity, and acceleration motion signals.



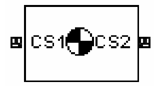
: "Joint Sensor" block measures linear/angular position, velocity, acceleration, computed force/torque and/or reaction force/torque of a joint primitive.



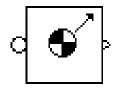
: "Revolute" joint block represents one rotational degree of freedom. It can be driven by the "Joint Actuator" block and its motion can be measured by the "Joint Sensor" block if the blocks are attached to this block.



: "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.

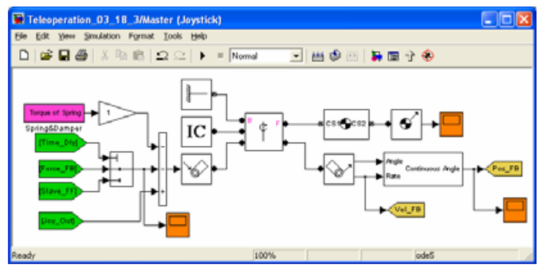


Figure 2. Master (joystick) sub-system window

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."

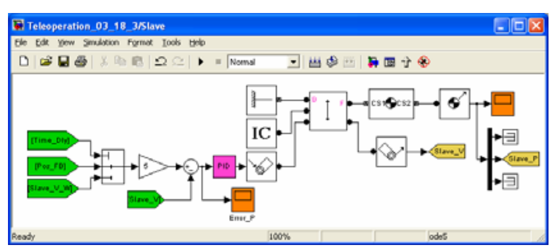


Figure 3. Slave sub-system window

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 with the environment and enables the force feedback information to be sent to the master by switching from zero input block to the “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 used to integrate the wave variable method into the communication line between the master and the slave. The amount of time delay is set through the “Time Delay” blocks.

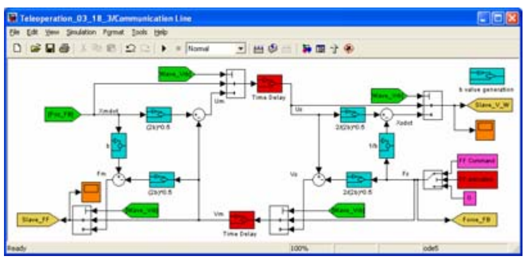


Figure 4. Communication line block window

The main control window of teleoperation is illustrated in Figure 5. The subsystems are marked with “Master (Joystick)” and “Slave.” The generation of time delay and the application of the wave variable method to the communication line are realized 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 master robot (joystick) motion 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 entitled “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 the application of the wave variable technique to the system with a constant time delay. This switch also generates an input, “Wave_Vrb”, for the switching in the “Communication Line” block.

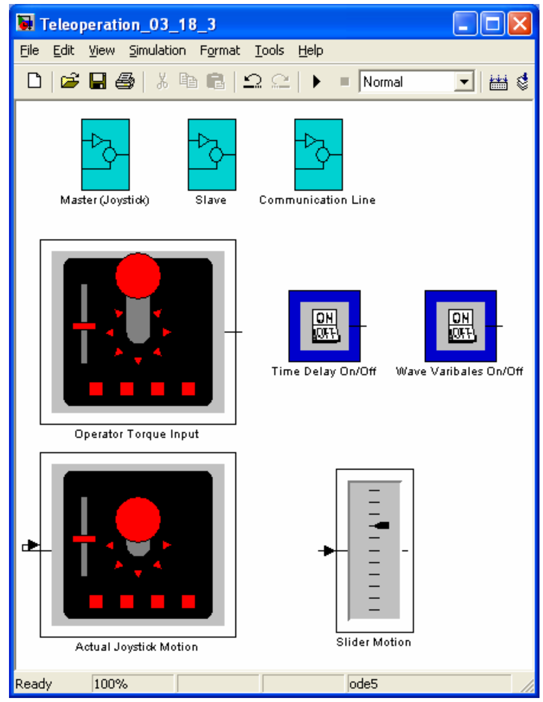


Figure 5. Main teleoperation interface window

Preliminary simulation results for teleoperation

The first simulation in this study is conducted for a communication line having no time delay, which will give an idea of an ideal case where the two sub-systems are coupled perfectly without any reason for instability (due to time delay). The second simulation is carried out for a time delay of 0.5 second and in the absence of wave variable technique. This simulation provides information on how time delay plays a role in the stability of teleoperation. Finally, the last simulation is done for a time delay of 0.5 second in the presence of wave variables to guarantee stability in teleoperation.

The scenario for each simulation is set for the operator to apply a steady torque to the master controller (joystick) to send a constant velocity command to the slave. The slave slider’s proximity sensor is set to 50 inches and therefore as it attempts to go beyond 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 limit of 50 inches due to the steady operator torque input.

Figure 6 is presented to depict the effect of wave variable method on the stability of teleoperation. The solid lines in 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 figure that when the wave variable method is not activated the slave motion oscillates without any damping to converge the motion to a steady state. As the wave variable method is activated, the motion of the slave is damped and therefore converged to a point just above the limiting value of 50 inches.

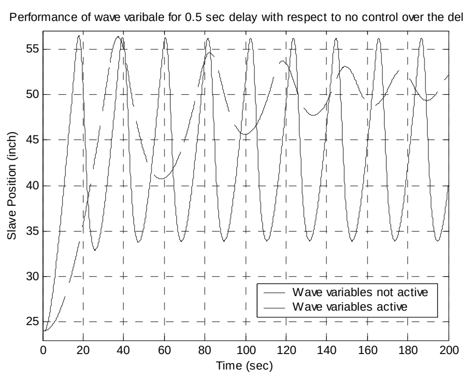


Figure 6. Effect of wave variable technique on a 0.5 second time-delayed teleoperation

While enhancing the stability of teleoperation with a constant time delay, the decrease in the manipulation speed caused by the application of wave variable technique can also be observed from the above figure. Figure 7 illustrates the slave motion for the cases with and without time delays. The wave variable method is applied to the teleoperation system when time delay is modeled.

Even if the wave variables are active for a constant time delay, rise for the oscillation magnitude with respect to the ideal teleoperation case can be observed from Figure 7. While the magnitude of the oscillations increases and manipulation speed decreases, in this simulation, wave variables still achieves the task of a stable response for a constant time delayed teleoperation.

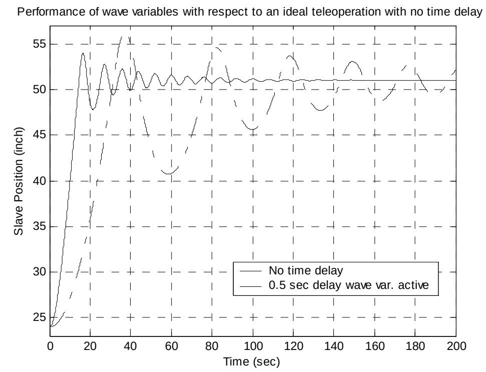


Figure 7. Side effects of wave variables with regard to the ideal teleoperation with no time delay

When selecting the wave impedance for the wave variables controller, one should be very careful not to make the teleoperation system unstable. Tuning of the wave impedance term, *b*, enables the possibility to change the characteristics of the teleoperation system as it is observed in Figure 8.

As the wave impedance term increases, it is further observed that the oscillation magnitude increases while the oscillation frequency decreases. This means that an increase in the impedance term causes the manipulator to settle in steady state in a longer time period with larger overshoots in transition state. Also, as another outcome of this simulation, the wave impedance term should be selected in some range that will not cause instability. The range came out to be between 400 and 800 for the system simulated.

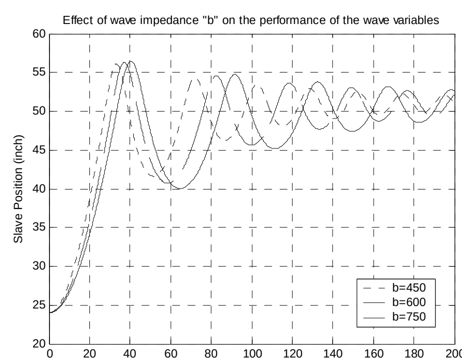


Figure 8. Performance variation of the wave variable technique due to the wave impedance

Conclusions

In this article, the theory of wave variable technique, modeling of a 1-DOF teleopeartion and three simulation results of this teleoperation system are presented. Although the main task is planned to be the same for each simulation, activation and deactivation of the wave variables in simulations provided a better understanding of the necessity of the wave variables in constant time delayed teleoperation.

The wave variables enhance the stability of constant time delayed teleoperation, but it tends to increase the magnitude of the overshoot and cause a decrease in the manipulation speed relative to the ideal case when no time delays are involved. Also, tuning of the wave impedance term for an optimum manipulation speed and overshoot is required.

The next step for the continuing study of wave variables will be the investigation of the effect of different time delay magnitudes on teleoperation, and how the wave variables method handles it.

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