Some Recent Approaches to Teleoperation in the Presence of Time Delay

Marc Alise and Rodney G. Roberts
Department of Electrical Engineering
FAMU-FSU College of Engineering

Abstract - **In this article we survey some of the recent work dealing with time delay when found in a teleoperation system. We develop a SIMULINK model for both a single degree of freedom and a multiple degree of freedom bilateral teleoperation system. We will then implement the wave variable method in both systems and compare the simulation results to those when the system is without any delay. We conclude with the next steps to generalize and hopefully optimize the wave variable method for systems with any amount of time delay.**

Keywords: telerobotics, time delay, wave variables

I. INTRODUCTION

Teleoperation systems are frequently used for many different reasons, handling toxic or harmful materials, dealing with remote environments such as undersea or space, and tasks that require extreme precision are just a few. An early use for teleoperation was to deal with toxic or nuclear waste that was potentially harmful to humans. Teleoperation provides a human-machine interface that allows people to controls robots at a large distance.

There are two master-slave teleoperation system types, unilateral and bilateral. Unilateral teleoperation does not include force reflection, and therefore there is no feedback for the system user. In most cases, the force feedback found in a bilateral system improves the teleoperation performance. This haptic interface provides a kinesthetic link between a human operator and a virtual environment. One way this force feedback was used was as a means to help pilots. Before bilateral systems were used, when pilots would use the joystick to move their plane, the delay would cause them to float back and forth around the desired final point. The forced feedback was introduced in order to give the pilot a better sense of how much force they needed to apply in the presence of a delay in the system.

One major problem that can be found in bilateral teleoperation systems is time delay. When the master and slave are located at a far distance from each other, the time delay is no longer negligible. In situations like the Internet where the time delay is unknown or varying, the system performance degrades even further. In the late 1980's Anderson and Spong [1] found that it is possible to stabilize a force reflecting teleoperation system that has a time delay. Later, Niemeyer and Slotine [9] worked with wave variables to further improve system stability. Wave variables are used in place of the more conventional power variables like velocity and force. It was found that when forces and velocities were transformed into wave variables and transmitted at both the master and slave sides, systems could remain stable even with some time delay. Even with all this and other research, the stability and the performance of a variable time delay system can still be further improved.

II. TIME DELAY AND INSTABILITY

Nearly all teleoperation systems will experience some time delay while operating. When the master and slave are close to each other this delay is usually negligible and can be compensated for with the correct controller. When the distance is increased greatly the time delay can no longer be ignored and will cause the system to degrade or to even become unstable. In situations including deep sea, outer space, and other long distance applications, time delay poses a serious problem.

Time delay in a control system introduces a phase lag which in turn degrades the system performance. In bilateral teleoperation systems information is sent from the master to the slave, and force reflecting signal is sent back. In these systems the communication delay appears twice and even further degrades the system. An example would be a system for controlling an airplane. The pilot uses the joystick to control the movement of the plane. There is a mechanical time delay introduced which can lead to pilot induced oscillations (PIOs). If the system was using a haptic interface and the pilot was receiving a force feedback, the time delay, if not compensated for, would cause even worse performance.

Time delays can cause even more problems in systems when the delay is not exactly known or if it is varying. In the latter case the delay usually fluctuates around a particular value, but there are also spikes where the delay greatly increases or decreases. When the spikes occur it is possible for the information to arrive out of order, causing serious problems. Due to the fact that the Internet is already in place, if a master station could use it to control its slave, the system would cost little or no money to set up.

III. TELEOPERATION

As mentioned earlier, there are two different teleoperation system arrangements; unilateral and bilateral. In the unilateral case the system is designed similar to an open loop controls system, i.e. there is no feedback. This system is generally not very difficult to build, but the applications are limited. One scenario where the unilateral system may be a good choice might be when the master and slave are in the same room and have a direct hardwire link between them. An operator that is in the same room as the slave robot can already see what is happening and may not need another type of feedback.

Even though the bilateral teleoperation system is harder to implement, it does allow for a much wider range of applications. In a basic bilateral setup, the master location sends information to the slave location while at the same time the slave is sending back different information. A basic illustration of this is shown in Fig. 1.

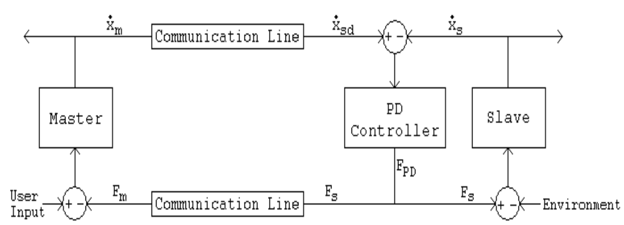

Fig. 1. Single degree of freedom bilateral teleoperator.

Fig. 1 is an illustration of a haptic bilateral teleoperation system. In this case the feedback in the system is in the form of a force that the user will feel. As long as there is no time delay present this system performs well, i.e. the slave's behavior tracks that of the master, both with force and velocity. Fig. 2 shows the results of the single degree of freedom system without any delay in the communication line. The input force to the master was 1. Fig. 2 shows that without any delay, all aspects of the master and slave are alike.

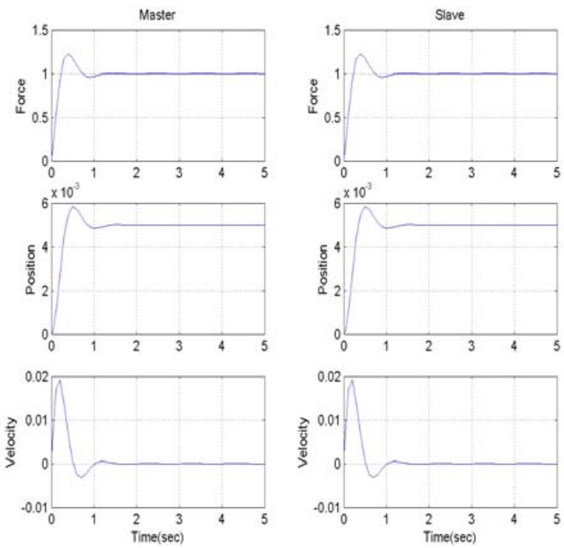

Fig. 2. SDOF bilateral teleoperator with no time delay.

Once a small amount of delay is introduced into the system, the performance will quickly degrade, and the system may even become unstable. As shown in Fig. 3, the position and velocity of both robots along with the force felt has gone unstable. It can also be seen that due to the time delay there is a slight difference between the positions and velocities of the master and slave. If the system can be implemented with little time delay and there is some other form of control added to deal with that delay, a bilateral teleoperation system can be used to perform many different tasks.

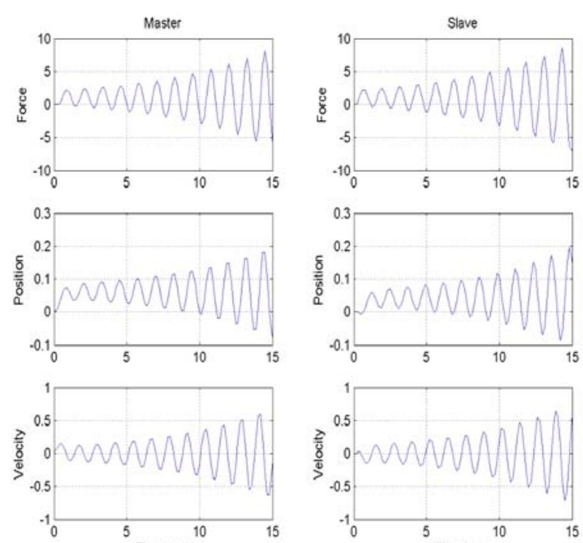

Fig. 3. SDOF bilateral teleoperator with 400 msec time delay.

IV. WAVE VARIABLES

Due to the effects of time delay in some teleoperation systems, it is important to find a way to provide extra control between the master and the slave robots. In the 1980's, Niemeyer and Slotine [9] worked on a passivity-based method involving wave variables that take the place of the original power variables. The general theory of passivity, when dealing with a bilateral teleoperation system, ensures that the energy being sent from the master to the remote system is always greater than or equal to the energy being sent back from the remote system to the master. In a system where force and velocity are transmitted as shown in Fig. 1, passivity requires that the product of the force and velocity at the master side, or power in, minus the same combination at the slave site, or power out, must be a positive value. For this to be true, the communication link along with the slave system would have to be lossless or dissipative. Assuming that the slave system is already passive, one is forced to find a way to change the communication line so that the above criteria are still met. Niemeyer and Slotine were able to guarantee that the passivity requirements were met, and the overall system would remain stable for any amount of constant time delay by replacing the standard communication line with that shown below in Fig. 4.

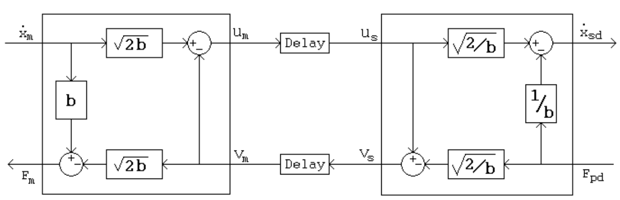

Fig. 4. SDOF bilateral wave-variable transformation

Wave variables provide an alternative means for encoding information. The transforms that are required are very simple and still preserve all of the original information. The nature of these transforms, in combination with time delays, introduces damping elements that allow the system to perform within the levels defined by the delay limitations. In the configuration shown in Fig. 4, velocity and force are transformed into wave variables before they are transmitted across the line. Once the wave variables are received the velocity and force information is extracted. Also, it must be noted that Niemeyer defined right moving waves to be positive and left moving waves to be negative [8]. Therefore, the equations that govern the transmission process are

$$u_s(t) = u_m(t-T)$$
$$v_m(t) = v_s(t-T) \quad (1)$$

The wave transformation equations for the left wave junction are

$$u_m(t) = \frac{b\dot{x}_m(t) + F_m(t)}{\sqrt{2b}}$$
$$v_m(t) = \frac{b\dot{x}_m(t) - F_m(t)}{\sqrt{2b}} \quad (2)$$

and the equations for the right wave junction are given by

$$u_s(t) = \frac{b\dot{x}_{sd}(t) + F_{pd}(t)}{\sqrt{2b}}$$
$$v_s(t) = \frac{b\dot{x}_{sd}(t) - F_{pd}(t)}{\sqrt{2b}} \quad (3)$$

where b is the damping factor for the transformations. These transforms are unique and invertible, i.e. one to one, which are also known as bijective transformations. There is no information lost or gained when the information is encoded in this way.

To show the wave variables in action, we will use the same system parameters that generated Fig. 2 and 3. However, now we will include the wave transformations before and after transmission, and we will send wave variables (u, v) instead of power variables, $(\dot{x}, F)$ over the transmission lines. Also we will implement the wave variables with a more useful form of equations (2) and (3) given by

$$F_m(t) = b\dot{x}_m(t) - \sqrt{2b}\,v_m(t)$$
$$u_m(t) = \frac{2b\dot{x}_m(t) - \sqrt{2b}\,v_m(t)}{\sqrt{2b}} \quad (4)$$

for the left side, and

$$\dot{x}_{sd}(t) = \sqrt{\frac{2}{b}}u_s(t) - \frac{1}{b}F_{pd}(t)$$
$$v_s(t) = \frac{\sqrt{2b}\,u_s(t) - 2F_{pd}(t)}{\sqrt{2b}} \quad (5)$$

for the right side. Due to the fact that only wave variables are passed through the communication lines, the system should no longer become unstable. As can be seen in Fig. 5, the system no longer becomes unstable, and the force, position, and velocity of the slave follow those of the master quite well. If these results are compared to the original system without any time delay present, it can be seen that the general trends are preserved; however, there is a slight degradation in performance, both with respect to peak overshoot and settling time. Overall, even with these performance issues it is obvious that the system with the wave variables present is much more conducive to the needs of a bilateral teleoperation system.

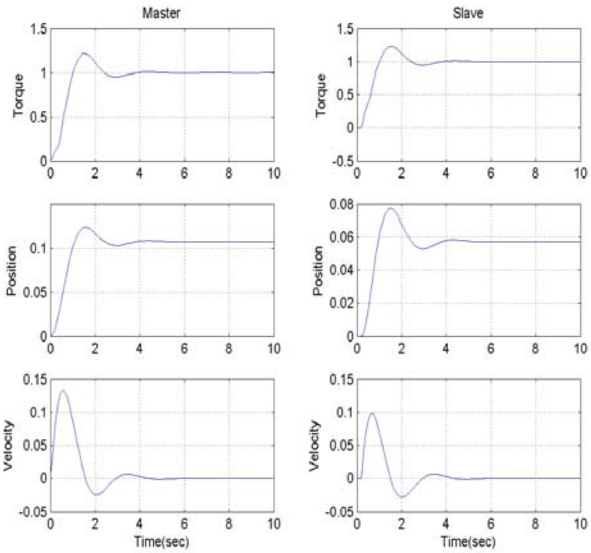

Fig. 5. SDOF wave-based bilateral teleoperator with 400 msec time delay.

V. MULTIPLE DEGREES OF FREEDOM

In order to implement the wave variable method on a system that has more then one degree of freedom, the equations for the transforms must be generalized. Now instead of a scalar transformation, a matrix transformation is needed to couple the different degrees of freedom. Writing the transformation equations from before in a more general form yields

$$u_m(t) = A_w \dot{x}_m(t) + B_w F_m(t)$$
$$v_s(t) = C_w \dot{x}_s(t) - D_w F_{pd}(t) \quad (6)$$

Also for v_m and u_s the equations are

$$v_m(t) = C_w \dot{x}_m(t) - D_w F_m(t)$$
$$u_s(t) = A_w \dot{x}_s(t) + B_w F_{pd}(t) \quad (7)$$

where A_w, B_w, C_w, and D_w are $n \times n$ scaling matrices and n is the number of degrees of freedom of the teleoperation system. Now that we have these new scaling matrices we need to define them in such a way that passivity is maintained. To accomplish this we will define the power-flow at each side to be

$$\dot{x}_m^T F_m = \frac{1}{2} u_m^T u_m - \frac{1}{2} v_m^T v_m \quad (8)$$

for the master side and

$$\dot{x}_s^T F_{pd} = \frac{1}{2} u_s^T u_s - \frac{1}{2} v_s^T v_s \quad (9)$$

for the slave side. By substituting equation (7) into equations (8) and (9), and doing some matrix arithmetic [7] it follows that

$$A_w^T A_w = C_w^T C_w$$
$$B_w^T B_w = D_w^T D_w \quad (10)$$

and also that

$$I = \frac{1}{2}(2A_w^T B_w + 2C_w^T D_w). \quad (11)$$

Now equations (4) and (5) from before can be rewritten by substituting in the scaling matrices. This results in

$$F_m = D_w^{-1} C_w \dot{x}_m - D_w^{-1} v_w$$
$$u_m = (A_w + B_w D_w^{-1} C_w)\dot{x}_m - B_w D_w^{-1} v_m \quad (12)$$

for the left side, and

$$\dot{x}_{sd} = A_w^{-1} u_s - A_w^{-1} B_w F_{pd}$$
$$v_s = C_w A_w^{-1} u_s - (C_w A_w^{-1} B_w + D_w) F_{pd} \quad (13)$$

for the right side. It can clearly be seen from equations (12) and (13) that the scaling matrices must be non-singular. Also to satisfy equations (10) and (11) there are a number of choices, the simplest being

$$A_w = C_w$$
$$B_w = D_w. \quad (14)$$

Using this relationship equation (11) will now reduce to

$$I = 2A_w^T B_w. \quad (15)$$

Keeping all of the above equations in mind, there is now a way to implement the wave variable method in a multiple degree of freedom teleoperation system while also satisfying all passivity requirements.

Now that the communication lines are set up using the wave variable method, a robot must be chosen in order to simulate the entire system. The performance will be tested using a 3 degree of freedom linear robot. The equation of motion for both the master and slave manipulators is given by

$$\tau_{pd} = J_s \ddot{\theta} + B_s \dot{\theta} \quad (16)$$

where τ_{pd} is the input torque, J_s is the desired 3x3 constant positive definite symmetric inertia matrix, and B_s is the damping matrix with the same qualities as J_s. Now that we have both the wave variable and the motion equations necessary to complete the system, we can finally simulate a 3 degree of freedom bilateral teleoperation system.

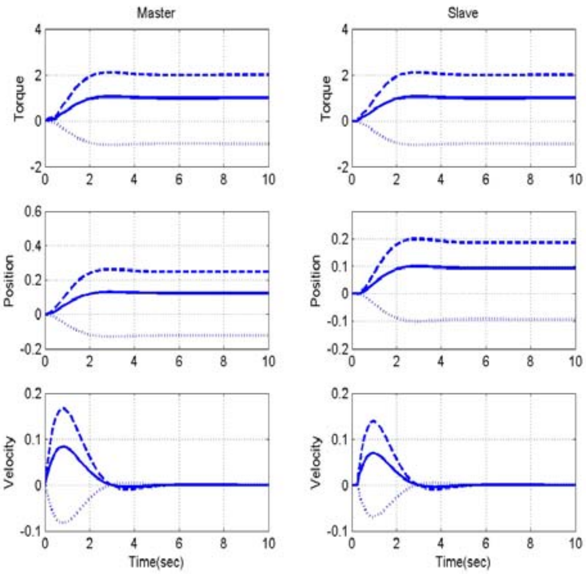

Fig. 6. MDOF teleoperation system simulated with a 1sec total time delay

As can be seen in Fig. 6, the linear multiple degree of freedom system behaves similarly to that of the single degree system. The input torques to the different dimensions were 1, 2, and -1, respectively. The slave manipulator was able to match the performance of the master manipulator with respect to torque position and velocity. Also, in less then 5 sec all dimensions had reached their steady state values. Due to the nature of the wave variable method, it can be shown that with a little parameter tuning, the system will stabilize for any amount of constant time delay.

VI. Conclusion

This research has focused on controlling robotic teleoperators in real time in the presence of time delay. We began by discussing some of the past and present situations when teleoperation could be used. Due to the fact that people would like to be able to use telerobotics over larger distances the effects of time delay have become more prominent. This research specifically focuses on bilateral teleoperation where there is a force feedback. This haptic interface allows the user at the master robot to have a kinesthetic link with the telerobotic system.

In the first section, the effects of time delay on a teleoperation system were discussed. To stabilize the system in the presence of time delay, another form of control must be introduced. We have concentrated on using the wave variable method as the extra form of control. As described earlier, the wave variable method transforms power variables like forces and velocities into wave variables. This method can be used to stabilize both single and multiple degree of freedom systems. We started by explaining how the method works in a SDOF system, and how any amount of time delay can be dealt with. Simulations were shown in order to prove the feasibility of using the wave variable method to stabilize a single degree of freedom system.

The last section described a method for applying the wave variable transforms to a multiple degree of freedom system. The equations necessary to couple and transform a multiple degree of freedom telerobotic system are given. Once the wave transformations and equations of motion are combined, the multi degree of freedom teleoperation system can be realized. Results are given that show the effects the transformations have on a MDOF system.

The next step in this research is to begin to deal with variable time delay that can be present in certain systems. By introducing variable time delay into the simulations, we will be able to determine how the systems would function if connected over the internet. To be able to deal with the varying delay we will need to add more to the system. Future simulations will include a Kalman filter or some other predictor in order to help stabilize the system. Also, some other regulators will be added in order to incorporate the predictor. The final step will be to build a fully functional master and slave robot, and then to connect the two through the internet to see if the simulations match the actual results. If a complete bilateral teleoperation system can be built and controlled though the internet we will have the means to test out many telerobotic situations.

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