Command Filtering and Path Planning for Remote Manipulation of a Long Reach Flexible Robot

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Abstract

Long reach manipulators are characterized by their light weight and large workspace. In order to fully utilize this workspace under teleoperated commands, motion amplification must exist between the master robot motion and the commanded motion of the slave robot. Unfortunately, this limits the accuracy with which an operator is capable of remotely executing a task. To extend the capabilities of our long reach testbed, our work focuses on the fusion of autonomous and teleoperated commands. This combination provides full use of the robot's workspace without requiring large motion amplification between a master and slave robot.

Combining autonomous and teleoperated commands provides the potential for large variations in the commanded momentum of the flexible robot. These variations excite the lightly damped, low resonant frequencies associated with these manipulators. This phenomenon provides the motivation for further investigation on the effect of joint control and path planning techniques on the tracking performance of flexible robots. Two techniques are proposed to reduce the vibration during sudden stops in the commanded motion of a flexible manipulator. First, a new command filtering approach that permits shorter delay times than standard input shaping methods is presented. Next, we propose dynamic alteration of the desired trajectory. Our investigation shows that filtering techniques exhibit an oscillatory response, more so than standard PD control algorithms, during hard stopping conditions. However, the shorter time delay filtering algorithm has less vibration than standard input shaping techniques. Furthermore, any vibration may be eliminated by commanding the robot to decelerate instead of immediately stopping the motion. Analysis and experimental results are provided.

1. Introduction

The advantage of long reach manipulators has been well documented over the past twenty years [3], [15]. These robots are characterized by their large workspace and light structural weight. However, this reduction in structural mass results in lower natural frequency values. Therefore, these robots have a tendency to vibrate during the execution of tasks. This vibratory effect has led to a flurry of mechanical and control design concepts. Bayo [2] and Kwon [8] showed fast response with little vibration by using inverse dynamic techniques. Alberts [1] showed that these techniques, in combination with passive damping on the elastic links, can reduce the magnitude of a broad band of frequencies during slewing motions. Unfortunately, the inverse dynamics technique requires an accurate definition of the robot's dynamic equations of motion which may prove difficult for multi-link robot systems. More recently, input shaping [13] and command filtering [11] techniques demonstrate reduced oscillatory effects without the sensitivity to modeling errors experienced with inverse dynamic techniques. Furthermore, Magee has shown that filtering techniques applied to a rigid manipulator attached to the end of a long reach flexible robot reduces the residual vibration of this combined system while still performing meaningful tasks [12].

Recently, attention is shifting to the utility of such systems for complex problems associated with handling hazardous materials [7]. Preliminary experiments using force reflecting teleoperation of flexible robots illustrate a few problems that exist during simple contact tasks [10]. The large workspace associated with these robots requires motion amplification between the master and slave robots. This scaling reduces the positioning accuracy that is necessary during contact tasks. Alternative techniques are sought that provide the advantage of teleoperation without requiring the operator's constant interaction through teleoperation or large motion amplification. First, a new approach is described to seamlessly combine both autonomous and teleoperated commands. Autonomous commands provide course positioning of the robot in its workspace. Teleoperated commands are superimposed on these commands to provide a perturbation from the desired path of the robot. In essence, the teleoperated commands permit the operator to execute articulated maneuvers while the autonomous component takes care of globally positioning the end of the robot.

Experiments show that the flexibility of these robots permits vibration during the transition between these two modes of operation. This investigation examines control techniques and trajectory generation methods in an attempt to isolate this difficult problem. Our investigation compares the performance of two control techniques, PD and command filtering, as well as an adaptive bang-bang path generator.

2. Seamless Transfer Between Autonomous and Teleoperated Commands

Methods are sought that permit the combination of both autonomous and teleoperated commands for manipulation. Our approach consists of treating teleoperated commands as perturbations from the command trajectory provided by an autonomous path planner. This approach differs slightly from the techniques described by Guo [5]. They proposed event-based planning and control as a means of fusing autonomous and teleoperated commands. Their system contains four basic functions: Stop, SlowDown, SpeedUp, and Orthogonal. The commands from the master robot, a spaceball in their system, provide velocity modifications to the command trajectory of the slave robot. Our approach is slightly different in that commands from the master robot consist of position modifications to the command trajectory of the slave robot. This approach permits easy implementation of force reflection but requires careful consideration during the transition between velocity and position commands.

Our testbed, described by Book [4], requires a position amplification of 7:1 between master and slave robots. Scaling provides a comfortable match between the slave robot's workspace and the human operator. For pure teleoperated commands, end point accuracy is limited when using position based control schemes. This position amplification may be reduced by using autonomous commands for large motions and teleoperated commands for fine articulated manipulation.

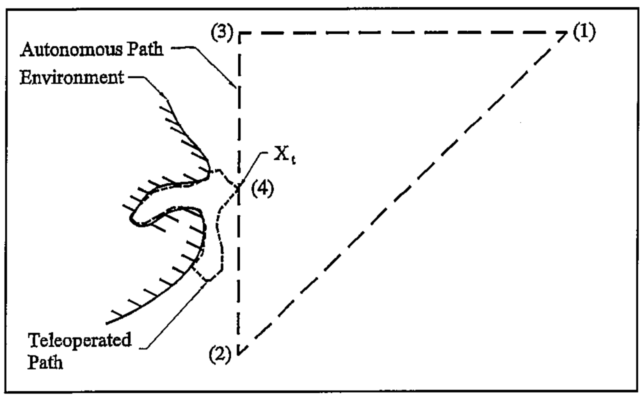

Figure 1. Autonomous and Teleoperated Task Execution

Consider the task illustrated in Figure 1. The robot uses autonomous commands for global positioning. However, when interaction between the robot and the environment is required, the system switches to a teleoperated mode. After completing the task, the control system transfers back to an autonomous mode and continues along its path. The following section describes how the switching between autonomous and teleoperated modes is accomplished and the problems that exist.

2.1 Impedance Controlled Master Robot

Our testbed consists of two kinematically dissimilar manipulators. The slave robot, RALF, is a two link, long reach manipulator. Each link is ten feet in length. Furthermore, the structural weight of the robot does not exceed 100 pounds while its payload capacity is approximately 60 pounds. The first natural frequency of this robot is about 4.5 Hz with a damping ratio of 0.01.

The master robot, HURBIRT, is a two degree of freedom impedance controlled robot designed for studies in the interaction of humans and robots [9]. The target impedance for the robot is defined as

$$M_t \ddot{x}_m + B_t \dot{x}_m + F_v = F_h + \tfrac{1}{A} F_e \qquad (1)$$

where x_m is the position of the master robot, F_h is the force applied by the human operator and F_e is the force applied by the environment. The target mass and damping matrices, M_t and B_t respectively, control the ease with which the operator moves the master robot. The virtual force, F_v, represents the repulsive force produced by deforming virtual fixtures in the robot's workspace. One example using the target impedance on a master robot is illustrated in Figure 2.

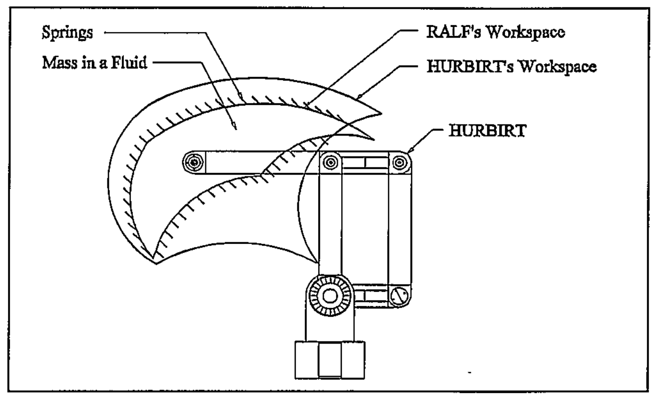

Figure 2. Virtual Walls for Bilateral Teleoperation

Since the workspaces of the master and slave manipulators are dissimilar, simple tasks such as moving the slave robot to its home position prove to be difficult by visual cues alone. Virtual walls are used to constrain the motion of the master robot to the scaled workspace of the slave robot. The target impedance of the master robot, using the same philosophy of superimposing impedances described by Hogan [6], is augmented with virtual walls that constrain the operator from commanding the slave robot outside it's workspace. Four compliant circles replicate the limits of the slave robot's workspace mapped inside the master robot's workspace. If the operator manipulates inside the scaled slave robot's workspace, the robot effectively "feels" like a mass moving through a viscous fluid. However, if the human attempts to command the robot outside it's workspace, the virtual walls attempt to push the operator back into the workspace. Position commands from the master robot to the slave robot are scaled by the amplification, A (for our testbed, $A = 7.0$),

$$x_s = A x_m \qquad (2)$$

where x_s is the position of the slave robot. The operator maneuvers the robot about its workspace tracing the trajectory to follow during autonomous manipulation.

During autonomous motion, a slightly different target impedance for the master robot is selected. The virtual force

$$F_v = K e^{-\alpha |x_m - x_0|} \left(x_m - x_0\right) \qquad (3)$$

is now a decaying potential well. This force can provide a localized equilibrium position on the master robot. The stiffness, K, controls the attractive potential while α controls the rate of decay of the force as the operator moves away from the equilibrium position. After the tip of the robot moves sufficiently far away from equilibrium, controlled by α, the robot behaves like a mass moving through a viscous fluid. Without any external forces applied to the master robot, the tip position of the master robot stays at the equilibrium position, x_0. If the tip position of the slave robot is within a defined radius of the equilibrium position, δ, the slave robot is under autonomous commands alone. A vector x_t denotes the current commanded position along a desired trajectory and k specifies the discrete time index. In purely autonomous mode, the current position of the trajectory is passed along to the slave robot as the new desired slave position x_s.

$$x_s = x_t[k] \tag{4}$$

If the human grabs the master robot and moves it away from the equilibrium position, the control system transforms from autonomous to teleoperated mode. First, the time index, k, associated with the command trajectory, $x_t[k]$, is suspended. The command to the slave robot now consists of two components, the last position on the trajectory and the perturbation provided by the human through the master robot.

$$x_s = x_t[k] + x_m - x_0 \tag{5}$$

Commands from the master robot provide a deviation from the commanded path. This approach provides a natural method of switching between autonomous and teleoperated commands. The operator needs only to grab the master robot and move it to switch between modes. Furthermore, after completing the teleoperated task, the operator needs only to move the master robot into the vicinity of the equilibrium position and release the master robot. The attractive potential field will draw the robot to the equilibrium position and the robot will then switch back to autonomous mode.

Of central concern now is the transfer between autonomous and teleoperated modes. The transition may require a dramatic shift in the commanded momentum of the flexible slave robot. Furthermore, when the operator completes the teleoperated task and the system switches back to autonomous mode, it must again accelerate to the command velocity. These issues are aggravated by the compliance associated with the long reach slave manipulator. A shift in momentum may excite vibration in the link structure of the robot. The following sections compare the performance of path planners and joint motion controllers and their influence upon the vibration of the slave robot during abrupt changes in momentum.

3. Command Filtering

The command filtering approach used here is based on pole-zero cancellation of the second-order equations of motion describing the flexible behavior. The three term filter takes the form

$$F(s) = \frac{1 - 2\cos(\omega_1 T)\, e^{\sigma_1 T} e^{-sT} + e^{2\sigma_1 T} e^{-s2T}}{1 - 2\cos(\omega_1 T)\, e^{\sigma_1 T} + e^{2\sigma_1 T}} \tag{6}$$

to cancel poles located at $s = \sigma_1 \pm j\omega_1$. This s-domain filter can be transformed to the digital domain with the transformation $z = e^{sT_s}$ where T_s is the inverse of the sampling rate of the discrete-time system. See [12] for a more detailed discussion of the command filtering method.

After identifying the poles of the system to be canceled, the delay time value, T, must be chosen. Previous filter design work has shown that an effective gain can be generated if the delay time is shorter than one-half the damped period of the second-order system. In standard shaping methods, the maximum gain is unity because the method is restricted to one value of delay time. In this work, we compare two different delay times. First, we use the delay time associated with Singer's input shaping technique (IS) [14]. For our system, the delay time is 0.091 seconds. Next, we use a general command filter (CF) which has a shorter delay time of 0.045 seconds. These filters are applied to the feedback error signal in a PD control scheme on the slave manipulator (i.e. RALF) in a similar manner as given in [11].

4. Trajectory Generators

When the robot switches between these autonomous and teleoperated modes, dramatic shifts in the commanded momentum of the robot exist. To reduce this effect, smooth blending between constant velocity trajectories and teleoperated commands are proposed. As an example, consider the case where the robot is commanded to depart from an existing constant velocity trajectory to teleoperated commands in an orthogonal direction. Simply switching from velocity to position commands excites lower modes of vibration in the compliant slave robot. An alternative approach is to smoothly blend these commands so the robot reduces its momentum before switching completely over to teleoperated commands. The problem also exists when transferring back fromteleoperated to autonomous commands.

4.1 BangBang Acceleration Profile

The first trajectory considered in this investigation is the Bang Bang acceleration profile. This profile accelerates at a maximum rate until the desired velocity is reached. When close to the destination, the robot decelerates at its peak rate.

$$v(t) = \begin{cases} A_{\max} t & t \le T_1 \\ V_d & T_1 < t < T - T_1 \\ V_d - A_{\max} t + A_{\max}(T - T_1) & T - T_1 \le t \end{cases} \tag{7}$$

$$T_1 = \frac{V_d}{A_{\max}} \qquad T = \frac{D}{V_d} + \frac{V_d}{A_{\max}} \tag{8}$$

Equation (7) provides the velocity profile with the time constants defined in Equation (8) where D is the distance of the path, V_d is the desired velocity and $A_{\max}$ is the maximum acceleration.

4.2 Seamless Transfer

To permit smooth transitions between autonomous and teleoperated states, dynamic alteration of the commanded path is required. To smoothly decrease the momentum of the robot when transforming from autonomous mode to teleoperation, the present velocity of the manipulator is first measured. Next, the parameters of the profile to go from this initial velocity to zero velocity are computed. This computation is easily accomplished within the sampling rate of the robot's controller. Thus, during the first few cycles of the teleoperated commands, the effective trajectory of the autonomous mode decelerates. This deceleration provides a smooth transition between autonomous and teleoperated modes. After completing a teleoperated task, the human moves the master robot to its equilibrium position. When the master robot reaches the equilibrium position, the current position of the slave robot is measured and the parameters of the trajectory are updated. Finally, the slave robot smoothly accelerates along its path towards its next target point.

5. Experimental Results

The following series of experiments illustrate the effect joint control and path planning have in the vibration response of a flexible robot during abrupt changes in the commanded momentum. Examples where this effect is relevant include the transfer between autonomous and teleoperated commands as well as emergency stop commands. The slave robot is commanded to follow a triangular path, illustrated in Figure 1. The horizontal and vertical portions of the path are one meter in length. The desired velocity along each segment of the triangle is 0.75 m/s with a maximum acceleration of 3.5 m/s^2. During the vertical line segment, at point (4) in Figure 1, the slave robot executes an abrupt stop. This effect can represent a transition produced through human intervention in teleoperation or an emergent stop situation.

Three joint control schemes are considered. First, the robot has a PD algorithm that is tuned to provide excellent joint tracking capabilities as illustrated in Figure 3.

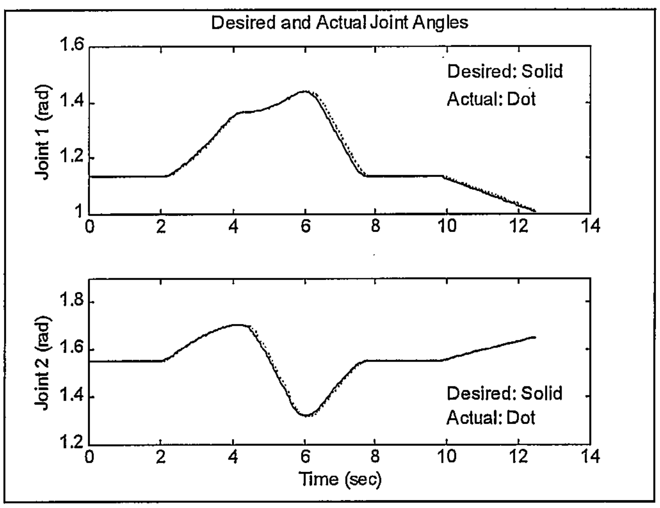

Figure 3. Joint Angle Response for Triangular Trajectory

The commands are then modified using either IS or CF, described in Section 3. Figure 4 illustrates the tracking performance of each of these algorithms. A landmark tracking system provides absolute tip position measurement. Evidently, some tracking error is due to the static deflection of the manipulators links. Joint controllers alone do not compensate for this effect.

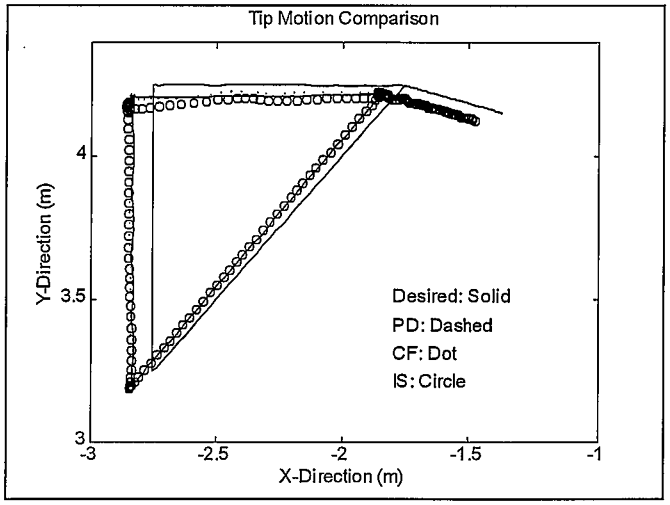

Figure 4. Tip Motion During Triangular Trajectory

Figure 5 illustrates the vibration produced in link 1 of RALF during the process of this task. It is evident that both filtering techniques reduce the level of vibration during motion. This reduction in vibration is also evident in the spectral response in Figure 6. Both filtering techniques reduce the magnitude of vibration of the first mode by approximately 20 dB.

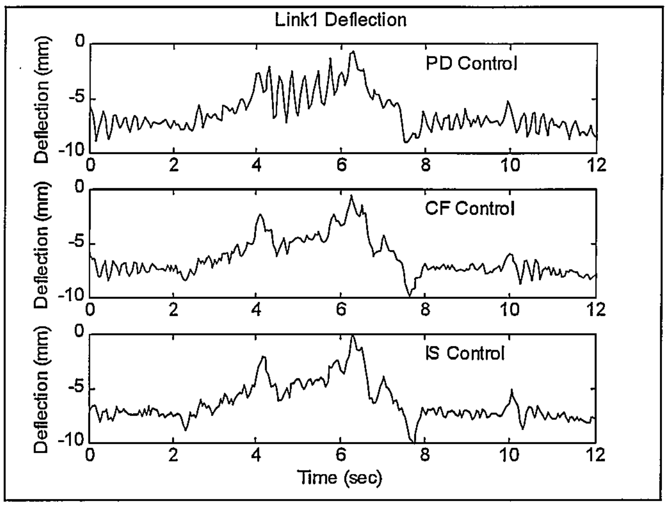

Figure 5. Link 1 Deflection During Triangular Trajectory

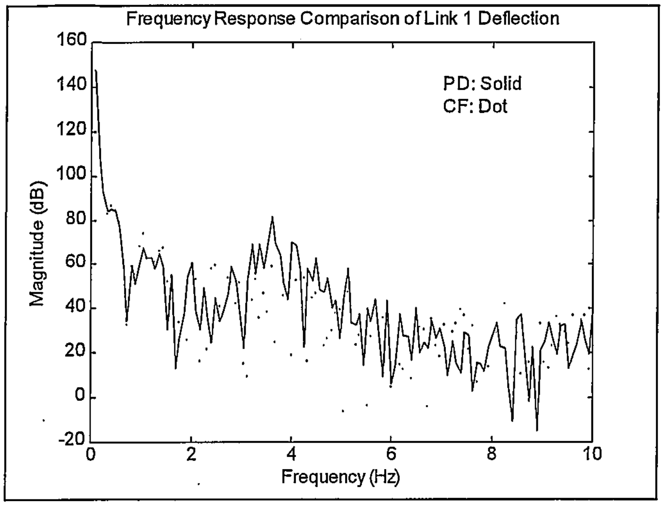

Figure 6. Frequency Response of Link 1 Deflection

Vibration is also evident during the hard stop, illustrated in Figures 7 and 8. This condition actually favors the PD controller over the filtering techniques. The increase in vibration for the shaping methods is due to the delayed response provided by the filtering process. The stop is initiated when the y position is 3.7 m. The PD controller overshoots the stopping point by 19 cm. The CF controller has a maximum overshoot of 31 cm while the IS has an overshoot of 52 cm. The CF controller produces less overshoot because it has an overall shorter delay time than the IS controller.

An alternative approach to stopping the momentum of the robot consists of commanding a smooth stop. This is accomplished by commanding the robot to execute the final stage of the velocity profile when the system is commanded to stop. Figure 9 illustrates the performance of the PD and CF controllers during this soft stop. It is evident that the magnitude of overshoot has decreased dramatically. The CF controller has a maximum overshoot of 1.75 cm while the PD controller has a maximum overshoot of 0.4 cm.

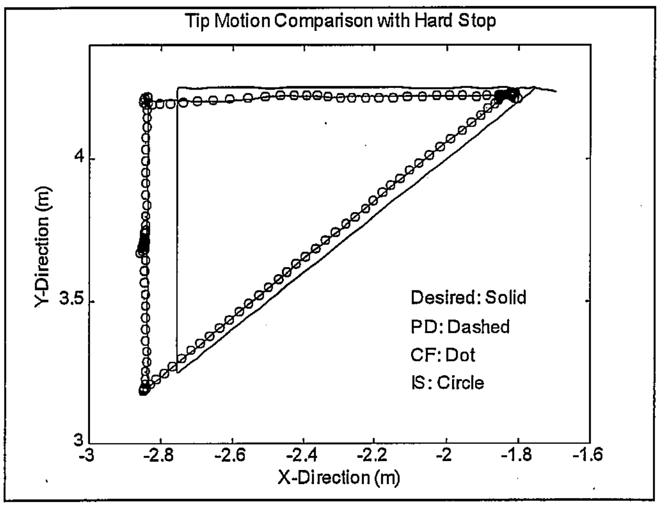

Figure 7. Tip Motion Comparison During Triangular Trajectory with Hard Stop

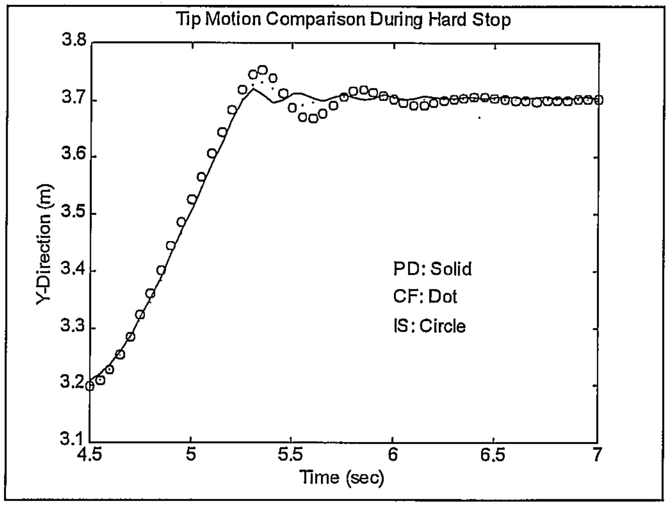

Figure 8. Tip Motion Comparison During Hard Stop

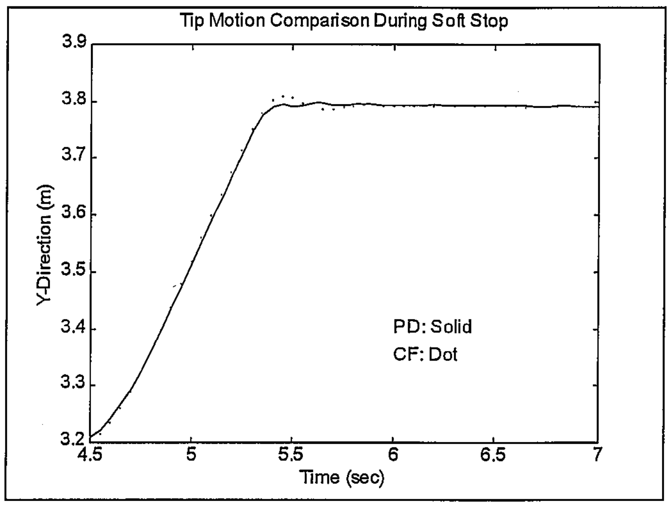

Figure 9. Tip Motion Comparison During Soft Stop

This reduction in vibration is somewhat deceiving because the actual commanded endpoint with the soft stop does not correspond to the point where the stop was initiated. While the approach reduces the magnitude of oscillation during a stop, it increases the error between the desired and actual robot stop positions.

6. Conclusions and Recommendations

This investigation presented a new approach for the teleoperation of long reach flexible manipulators. Experiments showed that command filtering techniques provide excellent vibration suppression during normal operations. However, if a dramatic shift in the commanded momentum of the robot occurs, the performance of the filtering techniques decreases. By shortening the filter's delay time, the amplitude of vibration was reduced.

Tapering the command trajectory also reduced the level of vibration during hard stopping conditions. Further investigation is necessary to determine what profile or delay time provides sufficient vibration absorption during slewing and hard stop trajectories. Also, these experiments suggest that some form of tip position feedback is necessary to compensate for the static deflection in the elastic robot.

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