Stabilization and control of teleoperation systems with time delays

by

Yongjun Hou

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Mechanical Engineering

Program of Study Committee:
Greg R. Luecke, Major Professor
Donald R. Flugrad
Atul Kelkar
Ping Lu
Judy M. Vance

Iowa State University

Ames, Iowa

2005

UMI Number: 3172222

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

# UMI®

UMI Microform 3172222

Graduate College
Iowa State University


This is to certify that the doctoral dissertation of

Yongjun Hou

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

To my wife, Yirong, and son, Andrew Fangyuan

For their love and support

# TABLE OF CONTENTS

# ACKNOWLEDGEMENTS

# ABSTRACT

Time delayed teleoperation has been one of the first and most challenging topics in robotic control. Although numerous methods have been developed by researchers all over the world during the last two decades, those methods have limitations or need special assumptions to be applied. With the development of the world-wide-web, teleoperation through the Internet sees a bright future. However, the constantly changing time delay in Internet data transmission brings a big challenge to Internet-based teleoperation. These time delays not only degrade the system performance, they also destabilize the teleoperation systems. In this work, a control scheme for teleoperation systems with time delay is developed based on the concept of passivity. This control method requires neither detailed knowledge of the manipulator systems nor the mathematical models of the environments, and it is applicable for any time delays. The model independence and time delay independence make the proposed control method well suited for teleoperation in the real world, which includes remote site explorations, tele-surgery, space explorations, and teleoperation through the Internet. The main contribution of this method is that it is less conservative than the traditional passivity based method. In our method, the passivity controller only operates when the system loses passivity, while in a traditional passivity formulation, the controller works at all times during operation and thus adversely affect the performance of the system.

Using the proposed control scheme, a sub-system is defined that is composed of the communication channel, slave robot and the manipulated environment. This sub system is treated as a one-port network component, and passivity theory is applied to this component to

assure stability. The energy flowing into the one-port network, in the form of the control command and the force feedback, is monitored. The passivity condition is violated when the net inflow of energy becomes negative, indicating that this component starts to "generate" energy, causing system instability. To reinstate the passivity of the network, a passivity regulator is activated to modify the feedback force to the master, and thus adjust the energy exchange between the master and the communication channel. Using the passivity regulator, the passivity of the system is maintained.

When this method is applied, only the information at the interface between the master manipulator and the communication channel is collected and observed, there is no need for accurate or detailed knowledge of the structure or timing of the communication channel. The method can make the system lossless regardless of the feedback force, the coordinating force controlling the slave joint motions, or the contact force. The approach presented here can stabilize the system regardless of the time delay, discontinuities with environmental contact, or discretization of the physical plant. Thus, unlike the traditional method, it will pose no problem when the environmental contact force is directly fed back rather than the coordinating force controlling the slave robot motion. The results of this work show that it is advantageous to use the measured environmental force as the feedback, providing superior performance for free motion and more realistic haptic feedback for the operator from the remote environment.

Along with computer simulations of a generic master-slave teleoperation configuration, experimental results are presented to validated the simulations and verify the proposed control scheme. A Microsoft Sidewinder force feedback Pro Joystick has been used as master and a PUMA 560 robot has been used as slave. The experimental results show that

the proposed method can stabilize the teleoperation system with any time delays and with any working environment. Both simulations and experiments show good position and force following performance.

# CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

## 1.1 Introduction

Teleoperation has been one of the first and most challenging applications of robotics[1].

It has evolved with the progress of technologies and the demand of applications.

Teleoperation started with Geortz and Thompson's demonstration of their first "master-

slave" remote control in 1954 [2, 3], and followed by Ferrel and Sheridan[4, 5] who focused

more on the system control aspects. In a traditional teleoperation system, there are two

manipulators, one of which, called master robot, is at the local site, while the other one,

called slave robot, is at the remote cite. The two robots are connected using a

communication channel. A person operates the master robot, and information about the

motion of the master is delivered to the slave robot, which performs these manipulations on

the remote environment according to the commands from the master. The master and slave

manipulators do not have to be at the different sites, but can be close to each other, as in the

case of using different motion scales, including micro-surgeries and nano-scale

manipulations [6, 7].

Generally speaking, there are two approaches to teleoperation, unilateral and bilateral

teleoperations. Unilateral teleoperation means the information is only transmitted from the

master to the slave, there is no information being sent back to the master from the slave.

Thus unilateral teleoperation is an open loop system, and there is no concern about the

stability of this type of system. Bilateral teleoperation requires the master to send not only motion information to the slave, but also needs the slave to send force information back to the master. The force feedback from the slave manipulator presents haptic feedback about the contact information between the slave and the environment to the operator, providing the human operator with increased awareness and realistic feeling. This added haptic information improves the operator's ability to perform complex tasks.

Another kind of teleoperation system uses only visual feedback of the slave to the operator. Strictly speaking, this type of teleoperation system is unilateral, and the operator does not have tactile sensation. However, the visual feedback does provide some information about the remote site and the whole system becomes an operator-in-the-loop closed loop system. This topic is also widely being investigated[8, 9]. The focus of this dissertation is on the force feedback bilateral teleoperation.

A typical force feedback bilateral teleoperation system is shown in Figure 1.1.
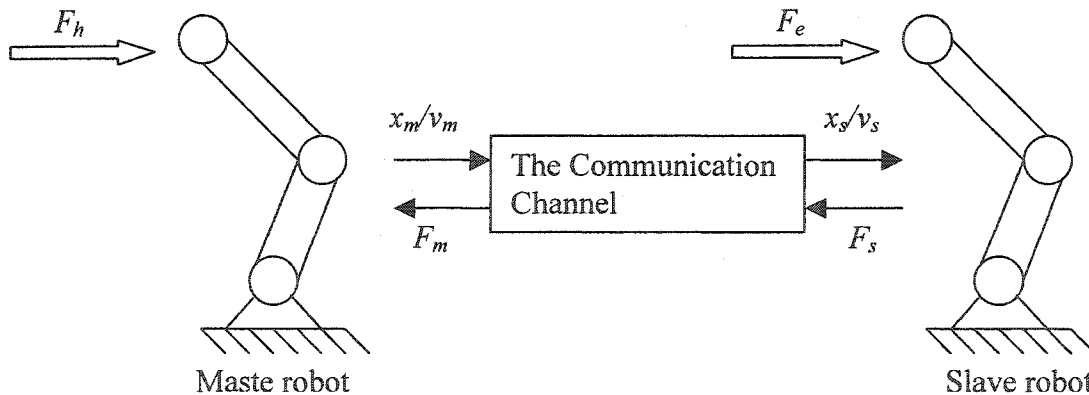


Figure 1.1 A teleoperation system

In the Figure, $F_h$ represents the force applied to the master robot by the operator. $F_e$ is the force exerted on the slave robot by the remote environment. $x_m$ is the position and $v_m$ is the velocity of the master, while $x_s$ and $v_s$ are the position and velocity commands for the slave . $F_s$ is the feedback force sent from the master to the slave. Ideally, this force is an exact duplicate of the contact force between the slave and the environment. In order to generate this force, a sensor is required that can measure and transmit this force to the master. Some researchers choose to use the coordinating force, which is the force output from the slave controller, to drive the slave. It has been shown that directly using contact force may destabilize the system even then there is no delay presents. $F_m$ is the command force of the master actuator.

During operation, when the operator moves the master, the velocity or/and position values of the master are sent to the slave through the communication channel. This information is used as the command to the slave controller, which drives the slave to follow the motion of the master. When there is any contact between the slave and the remote environment, the slave will send this contact force information to the master. The joint actuators at the master side will use this measured force information as command to generate a force such that the operator can accurately feel the contact.

Another configuration of teleoperation uses the coordinating force as feedback, instead of the actual contact force. Some research indicates that direct feedback of the contact force causes instability even when there is no time delay in the system[10]. Use of the coordinating force allows the dynamics of the slave controller, mainly the stiffness of the proportional term, to place an upper limit on the effective environmental stiffness, providing some advantage in stability during contact. However, use of the coordinating force also

means that he operator will feel the forces of operation required to overcome the dynamics of the slave, such as inertial and Coriolis forces. In chapter 6, the advantage of using the contact force as feedback will be discussed.

Bilateral teleoperation has been an active research topic for many years. It has wide applications in space explorations, underwater operations, hazardous environment manipulations, telesurgery and virtual reality. Transparency and fidelity are the two final goals to be achieved in bilateral teleoperation, while stability is the basic requirement that needs to be met for the system to be usable. When teleoperation is performed over a long distance, a time delay is incurred in the transmission of information from one site to the other. This time delay can easily destabilize a bilaterally controlled teleoperation system[4]. After stability, transparency is the major goal in teleoperation systems design. Transparency is defined as kinematic correspondence between the master and slave positions, and correspondence between the master and slave forces[11, 12], or a match between the impedance perceived by the operator and the environment impedance[13].

We have seen a significant development of the Internet in the last decade. It is readily available around the world, and does not require special purpose cables or connections. The Internet provides a convenient, inexpensive and accessible form of worldwide communication available to almost everyone. All these features make Internet an appealing media for teleoperation. If teleoperation can be implemented with good performance using the Internet, there will be no doubt that teleoperation will find wider applications, because of the wide access by the general public. However, Internet-based teleoperation also raises a great challenge to researchers. The time delay using Internet communications is fluctuating constantly, and communications may even be lost during temporary blackouts. The Internet

is considered to be a strongly connected network of computers, communicating with each other using packet switched[14] protocols. Since the packet exchange in the Internet is affected by the routes and handling policies at each node, the communication time delay is a random variable [15, 16]. It is difficult to make assumptions about the characteristics of the time delay in Internet communications. While there are random aspects, no simple statistical model had been developed. There is even no upper bound on the time delays in Internet communications, and the inter-arrival times of the communication packets cannot be estimated.

## 1.2 Literature Review

During the last fifteen years or so, many researchers have performed research on bilateral teleoperation control. Anderson and Spong[17-23] originally linked the observed instabilities to power generation in the communication channels, and employed passivity formalism and scattering theory, to stabilize the bilateral teleoperation with time delay.

Niemeyer and Slotine generalized Anderson and Spong's idea and named it wave-based teleoperation[24-28]. Using scattering or wave transformation, the bilateral teleoperation system can be stabilized for any constant time delay. But for variable time delay, the wave-based control does not have good performance, or may not even maintain stability. Later, Niemeyer and Slotine proposed a method [28] to send the integral of the velocity as well as the actual velocity through the communication channel, in an effort to maintain passivity and

compensate for position drifting. Because of the conservativeness of this method, the system performance was not satisfactory.

Leung and his colleagues[29] proposed a control method for force feedback teleoperation based on $\mu$-synthesis. The basic idea is to first design a controller for master manipulator, then design the controller for slave manipulator to force the slave velocity to track the master velocity. For constrained motion, the time delay was treated as perturbation, and the two delay blocks were lumped to a single block. $\mu$-synthesis was utilized again to design the controller for the constrained motion in hope not to affect the free motion. Block manipulations were performed to achieve optimal control design. In this case, the authors assumed the mathematical models of both master and slave manipulators are completely known, including the impedance of the slave side environment. This is not usually the case, especially for remote exploration of unknown environment, such as underwater or remote planetary operation.

Munir and Book[30] proposed a method to extend the application of wave based method to Internet-based teleoperation. They used a Kalman filter and a time forward observer to predict the wave variables and compensate the delay, and then employed an energy regulator to maintain the passivity. But in order for a Kalman filter to give satisfactory estimation, a fairly good model of the remote manipulator and the environment need to be available. In many cases, however, the remote model is not readily available, and this makes the application of their method limited.

Kosuge et al [31] proposed the "virtual time delay" method. In their method, they introduced extra artificial delay to compensate the actual time delay, such that the ultimate time delay in the communication channel becomes a constant which is equal to the time

delay in the worst case. They then utilized wave based method to stabilize the teleoperation system. While their method avoided the variable time delay limitations of the wave based method, and solved the stability and position drift problem, the overall performance was reduced significantly since extra delay was introduced on purpose.

Yokokohji et al [32, 33] proposed a method based on wave variables. In their method, they used an energy monitor to make the system passive under time-varying communication delay. They evaluated the ideal position deviation between master and slave manipulator, and adjusted the wave variables to approach the ideal position deviation. Their method requires a standard time delay that needs to be estimated using statistical methods.

Brady and Tarn[34] used a method called event based planning and control to implement a teleoperation system with variable time delay. It makes use of a sensor based action reference, in which operations commanded by the master robot are executed under the supervision of the slave robot controller, which makes decisions on the task to be executed on the basis of sensors readings. The method required the development of a supervisory paradigm based on the state space model, and a dynamic model of the robot was fused with the state space time-forward observer. The predictive nature of the architecture, as well as the virtual model, allow for a degree of transparency to the user of the remoteness of the working environment and the delays in the communication channels. Their method works at the price of increased knowledge of the remote manipulators and environment. Apparently, for a teleoperation system with an unknown dynamic model , their method cannot be applied directly.

Xi and Tarn[14] proposed a method using a non-time based action reference, based on the event-based planning and control theory[35]. The authors argued that, because of the

random communication delay, the synchronization of time-based action reference among different entities of the robotic system has been lost. Based on this argument, they introduced a non-time based action reference driven by sensory measurement. Since the new action reference is not directly related to time, it is independent of the time delay. Strictly speaking, their teleoperation system is not bilateral. They put the human in the loop and used visual feedback to close the loop. However, the human operator would not feel the force from the slave, and so it is not consistent with the definition of bilateral teleoperation.

In 2000, Elhajj, Xi and Liu[36] extended the application of the non-time based control to a teleoperation system with force reflection. Again they used the event-based control and chose the number of the forces felt by the operator. The connection was established using the event variable $s$. Instead of the contact force sensed by the end effecter, a virtual force was calculated and sent back to the master. Different sensors around the robot were used to detect objects. The virtual force was generated base on the distance between the object and the robot. In their system, the operator places the joystick in a certain position that corresponds to velocity vector. This vector is sent to the sensing unit on the robot. The sensing unit scans the environment and based on the position of the obstacles, the velocity is reduced and sent to the robot motors to be executed. The motors will execute the command, after that, the actual velocity is calculated. Then the actual velocity is subtracted from the original velocity required by the operator. This difference is sent back to the joystick motor to be played as force. To verify the effectiveness of their method, experiments were performed between US and Hong Kong. For this method to work, special sensors are needed to detect the distance from the robot end effecter to the environment. The operator will not be able to tell if the environment is soft or stiff, or what kind of tool the slave uses.

Later, Elhajj, etc.[37, 38] applied the event-based control on multi-site Internet based cooperative control. They also introduced the concept of event-based synchronization to cooperative control. Combining the Petri Net model and event-based planning and control theory, the new method provides an efficient way to model the concurrence and complexity of the Internet-based cooperative teleoperation. They use approaching velocity of other manipulators and the relative position from the environment to generate virtual force to feedback to the operators. They tested their method in a three-site test bed consisting labs USA, Hong Kong and Japan.

Oboe [15, 39] applied the real-time closed-loop control over the Internet in the Java Based Interface for Telerobotics(JBIT) system, in which Internet users can access and command a two-degree-of-freedom robot in real time, receiving both visual and force feedback. This method combined a buffering mechanism[31] and a predictor, in an effort to handle the delay variation and random packet losses. By using a predictor, it improved the system performance compared to a system with only a buffer mechanism, but again, this method requires the dynamic model of the robots to be applicable.

Hashtrudi-Zaad and Salcudean[40] investigated the issue of transparency in time-delayed teleoperation. They discussed the advantages provided by local force feedback and presented three-channel control architectures that are perfectly transparent under ideal conditions. In their research, they concluded that delayed kinematic correspondence is achievable when only either of the operator or the environment exogenous input is nonzero.

Cavusoglu et al[41] studied the teleoperation controller design for haptic exploration and telemanipulation of soft environment for the application of telesurgery. They introduced a

new measurement for fidelity in teleoperation, which quantifies the ability of the teleoperation system to transmit changes in the compliance of the environment.

Hannaford and Ryu[42] proposed a method to control haptic interfaces using the so-called time-domain passivity control. In their method, they used a passivity observer to observe the passivity of the one-port network system. If the passivity is lost, a passivity controller will be activated and a dissipative component will be used to dissipate the excessive energy in a single sampling period. The authors have shown both in simulations and in experiments that their method can stabilize the system when hard contact is involved. This method does not require the models of the system, and only dissipation is needed for optimum performance. But the added performance due to modeling external dissipation appears to be small. Thus this method works well without any parameter estimation. One limitation of this method is that, when operating in different environments, there will be some problems. If the manipulator has been operating in a very dissipative environment, which means an environment that dissipates a large amount of energy, the PC will not operate until a corresponding amount of active behavior is observed.

Ryu, Kwon and Hannaford[43, 44] extended the application of passivity based control method to bilateral teleoperation. Instead of using a one-port network component, they used a two-port network component to model the communication channel. They maintain the passivity of the system by still using the passivity observer and passivity controller. They observe the energy at both end of the communication channel. Since their method requires the force and velocity information at both ends of the communication channel, it is not applicable to teleoperation with time delay.

# CHAPTER 2 BILATERAL TELEOPERATION

When an operator operates a bilateral teleoperation system, force feedback from the slave manipulator presents the contact information to the operator, and it can provides the human operator with increased awareness and realistic feeling, and thus improves the operator's ability to perform complex tasks.

Sheridan[45] gave detailed definition of teleoperators, telerobots and telepresence. A teleoperator is a machine that extends a person's sensing and/or manipulating capability to a location remote from that person. A teleoperator necessarily includes artificial sensors of the environment, a vehicle for moving these in the remote environment, and the communication channels to and from the human operator. In addition, a teleoperator may include artificial arms and hands or other devices to apply forces and perform mechanical work on the environment. The term teleoperation refers most commonly to direct and continuous human control of the teleoperator, but can also be used generically to encompass telerobotics as well. Telemanipulation is sometimes used as a synonym for teleoperation.

A telerobot is an advanced form of teleoperator the behavior of which a human operator supervises through a computer intermediary. That is, the operator intermittently communicates to a computer of information about goals, constraints, plans, contingencies, assumptions, suggestions and orders relative to a remote task, getting back integrated information about accomplishments, difficulties, concerns, and raw sensory data. The

subordinate telerobot executes the task on the basis of information received from the human operator plus its own artificial sensing and intelligence.

Telepresence means that the operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site.

## 2.1 The Basic Structure of a Bilateral Teleoperation System

A teleoperation system consists of a human operator, a master robot on which the operator are actually manipulating, the communication channels, a slave robot called teleoperator, and the remote environment on which the slave robot manipulates. A block diagram of a typical teleoperation system is shown in Figure 2.1
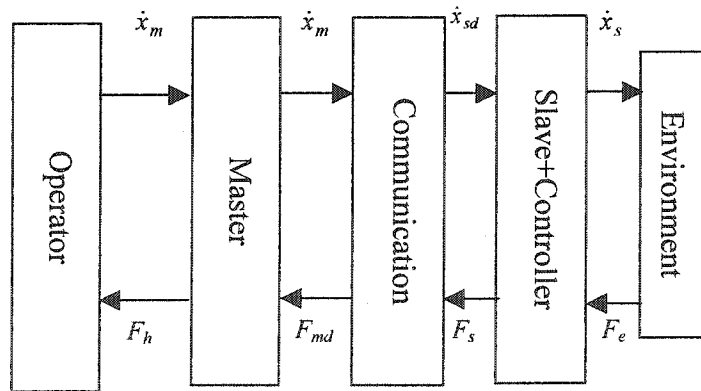


Figure 2.1 Block diagram of a teleoperation system

In this teleoperation system, the operator applied a force $F_h$ on the master robot, and the master robot moves at some velocity $v_m$ in response. The scenario is equivalent to the case in

which the operator gives a velocity command $v_m$ to the master. The real intention of the operator is to move the robot, not to merely apply forces on it. When being moved, the master robot sends a response force $F_h$ back to the operator. The velocity information of the master is transmitted, through the communication channel, to the slave. The transmitted velocity becomes the reference velocity $v_{sd}$ for the slave. Upon receiving the master velocity, the slave controller calculates the corresponding force $F_s$ to drive the slave manipulator to follow the received reference velocity. The calculated driving force, called coordinating force, is also sent back to the master through the communication channel, and becomes the desired master force $F_{md}$. Based on this desired force value, the master actuators generate the same amount of force and the operator can then feel it. When the slave robot contacts with the environment, the contact force $F_e$ will be reflected to the operator through the coordinating force $F_s$. But since only at steady state, $F_s$ has the same value as $F_e$, the force sensed by the operator includes the dynamic effect of the slave, especially when there is no contact, $F_e$ is zero, while $F_s$ is usually not.

Another configuration of a teleoperation system can be seen in Figure 2.2, where the major difference is the use of the coordination force of the slave in stead of the actual, measured environmental interaction force.
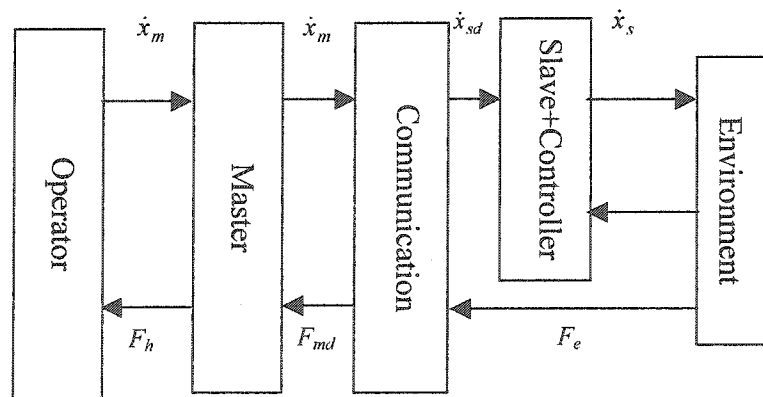


Figure 2.2  Block diagram of a teleoperation system with $F_e$ as feedback

Without special stabilizing mechanism, feeding back the contact force causes instability[10, 46]. In some previous work, researchers avoided using contact force as the feedback in order to achieve stability when no time delay presented. Instead, the configuration in Figure 2.1 has been used. Nevertheless, feeding back $F_e$, the true environmental forces, reflects the actual contact information from the slave manipulator, and that is what the operator really needs to feel. For the configuration in Figure 2.1, instability may occur during high velocity motion. Teleoperation using these two different configurations is discussed and compared in the following sections.

## 2.2 Ideal Teleoperation

In an ideal teleoperation system, the slave follows the motion of the master exactly and the master feels the exact amount of force applied by the environment to the slave. In this case, the connection between the master and the slave can be modelled as a spring with an infinite stiffness. It corresponds to a proportional controller with a proportion gain of infinity. Of course, infinite control gains cannot be implemented in the physical world, so this connection between the master and slave has a finite stiffness. Traditionally, a PD position controller is used to drive the slave to follow the motion of the master. Because the dynamics of the system produce finite response time, errors exist between the desired and actual position of the manipulator during transient response. Using the slave controller output as feedback, the traditional teleoperation system without time delays can be shown in Figures 2.3.
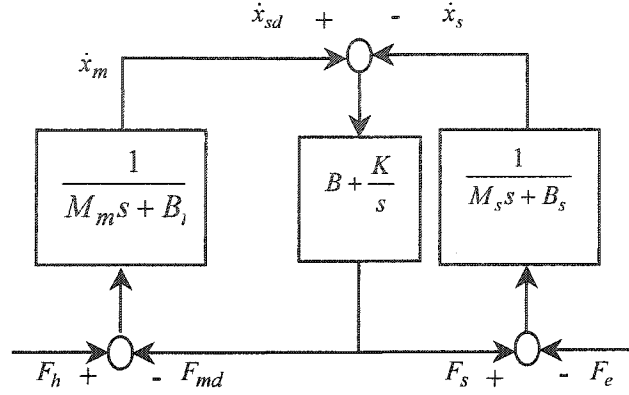
Figure 2.3 The traditional teleoperation system without

This system can be mechanically interpreted as shown in Figure 2.4, where the force control during teleoperation is shown as an equivalent spring and damper between the master and slave.
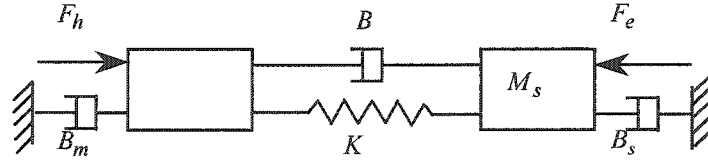


Figure 2.4 The mechanical analogy of a teleoperation system without time delay

Since a physical mass spring and damper system is a passive system, this configuration dissipates energy and does not generate energy. The PD controller has a spring damper physical equivalent, and it is thus also passive[47]. The concept of passivity will be treated in detail in Chapter 3.

The environment of a teleoperation system, based on different applications, can be a hard surface, viscous fluid, soft tissue, or a moving inertia. A hard surface is one of the most severe situations for contact control of robotic manipulator in general. Usually, a hard surface is modeled as a stiff spring, so it is a passive element. Because the discretization of a physical spring will make the spring lose passivity, the stability of hard surface contact control is also of concern[10, 42, 48].

In many contact situations, the joint compliances of the robot closed loop control system automatically limit the effective environmental stiffness, helping to stabilize the contact. To see this more clearly, we can refer to the mechanical analogy of the system in Figure 2.4. Figure 2.5 separates the elastic effect of the slave control system out. In the figure, $K_c$ is the controller proportional parameter. $K_e$ is the actual experimental stiffness. $x_d$ is the desired position and $x_s$ is the actual slave position. The effective stiffness is represented as

$$K = \frac{K_c K_e}{K_c + K_e}$$

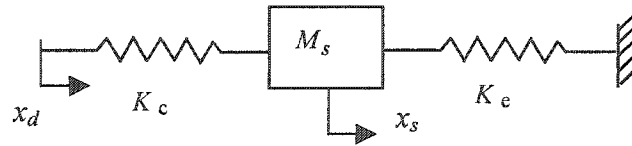apparently, for limited $K_c$, $K$ is always less than $K_e$



Figure 2.5  Effective environmental stiffness

# CHAPTER 3 PASSIVITY

Passivity is a powerful tool for analyzing a system and for designing control laws for it. It was originated from circuit network analysis, and has seen increasing popularity in control community. Passivity is a sufficient condition for guaranteeing the stability of the system. It is of the concept of input-output stability, while Lyapunov stability is of the trajectory of the system states. Passivity is a property that is independent of the notion of the states. It does not require state feedback to achieve the control objectives. The passivity concept can be applied directly to both linear and nonlinear control.

## 3.1 The Definition

*Definition3.1*[49]: A system is said to be passive if there exist a nonnegative scalar function *g(t)*, and a lower bounded scalar function *V(t)* that satisfies the relation

$$\dot{V}(t) = y^T u - g(t) \tag{3.1}$$

where *V(t)* is called storage function, *u* is the system input, and *y* is its output. If *g(t)* is a constant zero, the system is said to be lossless.

For a 1-DOF robot, the dynamic equation is

$$M\dot{v} + Bv = F \tag{3.2}$$

where $M$ is the mass of the robot, $B$ is the damping coefficient and $F$ is the force or torque applied on the robot including the robot motor torque.

Let the storage function $V$ be the kinetic energy of the robot, that is

$$V = \frac{1}{2}Mv^2 \tag{3.3}$$

Apparently, V has a lower bound of zero. The derivative of $V$ is

$$\dot{V} = Mv\dot{v} = Fv - Bv^2 \tag{3.4}$$

Obviously, the robot is passive according to the definition. Similarly, multi-degree of freedom robots can also be shown passive.

Since the environment can be modeled as a mass-damping-spring system, we have, for the environment

$$M_e\dot{v} + B_ev + K_e \int_0^t v d\tau = F \tag{3.5}$$

Choose the storage function as

$$V = \frac{1}{2}Mv^2 + \frac{1}{2}K_e \left( \int_0^t v d\tau \right)^2 \tag{3.6}$$

we have

$$\dot{V} = M_e v \dot{v} + K_e v \int_0^t v d\tau = Fv - B_e v^2 \tag{3.7}$$

Equation 3.7 shows that the environment modeled as a mass-damping-spring system is passive.

In particular if the environment is modeled as a spring, then it is also lossless. Let

$$V = \frac{1}{2}K_e \left( \int_0^t v d\tau \right)^2 \tag{3.8}$$

and

$$\dot{V} = K_e v \int_0^t v d\tau = Fv \tag{3.9}$$

A more physically oriented definition of passivity can be expressed for a general dynamic system. The system is said to be passive when it obeys

$$P = \dot{x}^T F = \frac{dE}{dt} + P_{diss} \tag{3.10}$$

where $E$ is the energy stored in the system, and $P_{diss}$ is the power dissipated by the system. For the system to be passive $P_{diss}$ must be non-negative. That means the system does not generate energy, instead, it either dissipates energy or just stores energy and releases it later.

In this definition of passivity, the "power" P is defined as the scalar product of the system input vector $u$ and the system output vector $y$. P does not necessarily to correspond to any physical power, and input vector $u$ and the system output vector $y$ do not always have to represent the so-called power variables—velocities and forces.

The passivity of the communication line with time delay can be tested using the definition of passivity. A general communication channel with time delay is shown in Figure 3.1
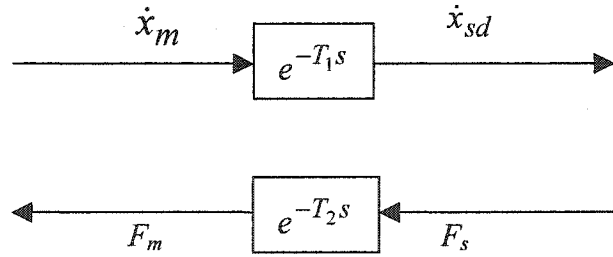


Figure 3.1 A typical two-way communication channel with time delay

In the Figure, $T_1$ and $T_2$ represent the forward and backward time delays respectively. They can either be constant and equal to each other, or they can be time varying. $\dot{x}_m$ stands for the velocity of the master manipulator, $\dot{x}_{sd}$ is slave velocity, $F_s$ is the force the slave sends back to the master, and $F_m$ is the force command to the master actuators. Because of the time delay in the communication channel, we have the relations

$$\dot{x}_s(t) = \dot{x}_m(t - T_1)$$

(3.11)

and

$$F_m(t) = F_s(t - T_2)$$

(3.12)

The passivity of the communication channel can be tested using the passivity definition

$$
\begin{aligned}
P &= \dot{x}_m(t) F_m(t) - \dot{x}_s(t) F_s(t) \\
&= \frac{1}{2}\left(F_m^2(t) + \dot{x}_m^2(t)\right) - \frac{1}{2}\left(F_m(t) - \dot{x}_m(t)\right)^2 + \frac{1}{2}\left(F_s^2(t) + \dot{x}_s^2(t)\right) - \frac{1}{2}\left(F_s(t) + \dot{x}_s(t)\right)^2 \\
&= F_m^2(t) - \frac{1}{2}\left(F_m(t) - \dot{x}_m(t)\right)^2 + \dot{x}_s^2(t) - \frac{1}{2}\left(F_s(t) + \dot{x}_s(t)\right)^2 \\
&\quad + \frac{1}{2}\frac{d}{dt}\int_{-T_2}^{t} F_s^2(\tau)d\tau + \frac{1}{2}\frac{d}{dt}\int_{-T_1}^{t} \dot{x}_m^2(\tau)d\tau
\end{aligned}
$$

(3.13)

Defining the stored energy $E$ and dissipated power as

$$E = \frac{1}{2}\left(\frac{d}{dt}\int_{-T_2}^{t} F_s^2(\tau)d\tau + \frac{d}{dt}\int_{-T_1}^{t} \dot{x}_m^2(\tau)d\tau\right)$$

(3.14)

and

$$P_{diss} = F_m^2(t) - \frac{1}{2}\left(F_m(t) - \dot{x}_m(t)\right)^2 + \dot{x}_s^2(t) - \frac{1}{2}\left(F_s(t) + \dot{x}_s(t)\right)^2$$

(3.15)

it is not difficult to see $P_{diss}$ can be either positive or negative depending on the values of the power variables. This proves that the communication channel with time delays is not passive. The time delays can be either constants or varying in the case. For the special case of zero time delay where $T_1 = T_2 = 0$, $F_m = F_s$ and $v_m = v_s$, both $E$ and $P_{diss}$ are zeros, and the communication channel is lossless.

## 3.2 Passivity of Networks

Passivity was originated from the circuit network analysis, and many physical systems can be modeled as general networks too. Passivity concept is powerful in system analysis, because the passivity of the whole system can be drawn from the passivity of the interconnected subsystems.

An n-port network is characterized by the relationship between effort F (force, voltage), and flow v (velocity, current). For a linear time-invariant (LTI) one-port network, this relation is specified by its impedance $Z(s)$ according to

$$F(s) = Z(s)v(s) \tag{3.16}$$

the relation is conveniently specified[50] by its *hybrid matrix, H(s)* according to

$$\begin{bmatrix} F_1(s) \\ -v_2(s) \end{bmatrix} = \begin{bmatrix} h_{11}(s) & h_{21}(s) \\ h_{12}(s) & h_{22}(s) \end{bmatrix} \begin{bmatrix} v_1(s) \\ F_2(s) \end{bmatrix} = H(s) \begin{bmatrix} v_1(s) \\ F_2(s) \end{bmatrix} \qquad (3.17)$$

*Definition 3.2*(Passivity)[19]: An n-port is said to be passive if and only if for any independent set of n-port flows, $v_i$ injected into the system, and efforts $F_j$ applied across the system

$$\int_0^\infty F^T(t)v(t)dt \geq 0 \qquad (3.18)$$

where $F = [F_1, F_2, \cdots, F_n]^T \in L_2^n(R_+)$ and $v(t) = [v_1, v_2, \cdots, v_n]^T \in L_2^n(R_+)$.

This condition only states that a passive n-port may dissipate energy but cannot increase energy of a system in which it is an element. In addition, an n-port is said to be lossless if and only if

$$\int_0^\infty F^T(t)v(t)dt = 0 \qquad (3.19)$$

In physical implementation, equations (3.18-19) need to be modified, since a physical system can break far before it reaches infinite time. Considering equation (3.10), if the system initial stored energy is zero, the upper limit of equations (3.18-19) should be changed to current time t. This means, up to the current time, the maximum energy the system can provide to the environment cannot exceed the energy it has absorbed from the environment. Then we have the condition for passivity as

$$\int_0^t F^T(t)v(t)dt \geq 0 \qquad\qquad (3.20)$$

and the condition for a system to be lossless as

$$\int_0^t F^T(t)v(t)dt = 0 \qquad\qquad (3.21)$$

From definition equation 3.18 through 3.21, one can see that to determine the passivity of a system, the only information needed is the flows injected into the system and the efforts applied across the system. The state changes inside the n-port are of no concern.

# CHAPTER 4 WAVE-BASED TELEOPERATION

During the last two decades, researchers have proposed many methods to stabilize the time delayed teleoperation system. The concept of passivity has been widely used to solve the problem. Among the numerous methods, wave-based teleoperation has been the most famous one. In this chapter, wave-based teleoperation control concept is briefly introduced, and the advantages and limitations of this method are also presented

## 4.1 Wave Based Teleoperation

Anderson and Spong[19] first proposed a method to stabilize the teleoperation systems with time delay. Their method is based on the theories of networks, scattering theory and passivity. In their method, they analogize the teleoperation system with electrical networks, and use scattering transformation to transform the power variables before they are transmitted to the other side through the communication line. Their method can stabilize the system with any constant time delays. And it is one of the most important methods in the teleoperation history. This method is briefly introduced here.

*Definition 4.1* (scattering operator): The scattering operator $S : L_2^n(R_+) \to L_2^n(R_+)$ is defined by

$$F - v = S(F + v) \tag{4.1}$$

where F is the effort applied across the system and v is the flow injected into the system.

Scattering operator maps effort plus flow into effort minus flow, where the flow is entering

the system's ports, and effort is measured across the system's ports

For LTI systems, the scattering operator S can be expressed in the frequency domain as a

scattering matrix S(s), where

$$F(s) - v(s) = S(s)(F(s) + v(s)) \tag{4.2}$$

***Theorem 4.1*** (passivity based on scattering theory): A system is passive if and only if the

norm of its scattering operator is less than or equal to one (for proof, see [19])

For a transmission line, the scattering operator relates the reflected wave $(F - v)$ to the

incident wave $(F + v)$. Its norm can be interpreted as the square root of the maximum power

gain for the element. Thus, it follows that for a passive element $\|S\| \leq 1$.

The control strategy used in their paper is

$$\tau_m = -B_m v_m - F_{md} \tag{4.3}$$

$$\tau_s = -B_{s2} v_s + F_s - \alpha_f F_e \tag{4.4}$$

where $F_s$ is called the coordinating torque and is given by

$$F_s = K_s \int (v_{sd} - v_s) dt + B_{s1} (v_{sd} - v_s) \qquad (4.5)$$

Note that the coordinating torque term $F_s$ and not the contact force $F_e$ is available to the communication block for transmission to the master. This is necessary to ensure the passivity of the slave block. Otherwise, contact instability will occur even when there is no time delay [10, 51]. The basic idea is to choose the control law so that the two-port characteristics of the communication block are identical to a two-port lossless transmission line.

Based on the scattering theory, and the representation of a lossless two-port transmission line, the control law is [19]:

$$F_{md}(t) = F_s(t-T) - v_{sd}(t-T) + v_m(t) \qquad (4.6)$$

$$v_{sd}(t) = v_m(t-T) - F_s(t) + F_{md}(t-T) \qquad (4.7)$$

In 1991, Niemeyer and Slotine[25] generalized the idea of Anderson and Spong, and proposed a more intuitive, physically motivated, passivity based formalism to stabilize the time-delayed teleoperation system. They introduced the notion of wave transformation. In their method, the power variables are not sent directly to the other side through the communication lines, instead, wave variables are transmitted. At the other end of the communication line, power variables will be decoded from the wave variables.

The wave variable based teleoperation is briefly introduced here, the readers are referred to [25].

The notion of wave scattering is closely related to the passivity formulation. It separates the total power flow into two parts, representing the power input and power output of the system. These two parts are then associated with input and output waves. The wave concept here is motivated by the physical concept of waves, but it is a general notion, without correlating to any physical waves and can be applied to any nonlinear systems.

The basic structure of wave-based teleoperation is shown in Figure 4.2
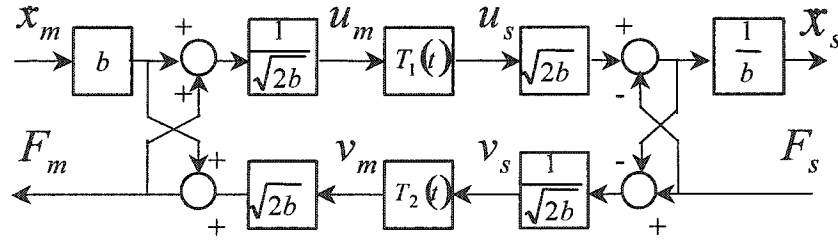


Figure 4.2  Configuration of wave-based teleoperation

The wave transformation is represented by

$$u = \frac{1}{\sqrt{2b}}\left(F + b\dot{x}\right)$$

$$v = \frac{1}{\sqrt{2b}}\left(F - b\dot{x}\right)$$

(4.8)

where $u$ represent the forward wave, and $v$ represent returning wave.  $b$ is named characteristic impedance of the communication channel.

The relations between the power variables and the wave variables can be expressed as

$$F = \sqrt{\frac{b}{2}}(u + v)$$

$$\dot{x} = \frac{1}{\sqrt{2b}}(u - v)$$

(4.9)

The passivity of the 2-port communication channel can be illustrated.

If the time delays are constant, the input power to the communication channel is

$$
\begin{aligned}
P &= \dot{x}_m^T(t)F_m(t) - \dot{x}_s^T(t)F_s(t) \\
&= \frac{1}{2}\left(u_m^T(t)u_m(t) - v_m^T(t)v_m(t)\right) \\
&\quad - \frac{1}{2}\left(u_s^T(t)u_s(t) - v_s^T(t)v_s(t)\right) \\
&= \frac{1}{2}u_m^T(t)u_m(t) - \frac{1}{2}v_s^T(t-T_2)v_s(t-T_2) \\
&\quad - \frac{1}{2}u_m^T(t-T_1)u_m(t-T_1) + \frac{1}{2}v_s^T(t)v_s(t) \\
&= \frac{d}{dt}\left[\int_{t-T_1}^{t} \frac{1}{2}u_m^T(\tau)u_m(\tau)d\tau + \int_{t-T_2}^{t} \frac{1}{2}v_s^T(\tau)v_s(\tau)d\tau\right]
\end{aligned}
$$

(4.10)

This shows that the system is not only passive, but also lossless.

The transparency of this configuration can be investigated by finding the relation between master velocity and slave velocity, and also the force sent back from the slave manipulator and the force information received by the master manipulator.

The relations between the velocities and forces of master and slave manipulators are

$$\dot{x}_s(t) = \frac{1}{\sqrt{2b}}\left(u_s(t) - v_s(t)\right) = \frac{1}{\sqrt{2b}}\left(u_m(t - T_1) - v_s(t)\right)$$

$$= \frac{1}{\sqrt{2b}}\left(u_m(t - T_1) - \frac{1}{\sqrt{2b}}\left(F_s(t) - \left(\sqrt{2b}u_s(t) - F_s(t)\right)\right)\right)$$

$$= \frac{1}{\sqrt{2b}}\left(2u_m(t - T_1) - \frac{2}{\sqrt{2b}}F_s(t)\right)$$

$$= \frac{1}{b}\left(F_m(t - T_1) + b\dot{x}_m(t - T_1)\right) - \frac{1}{b}F_s$$

$$= \dot{x}_m(t - T_1) + \frac{1}{b}\left(F_m(t - T_1) - F_s(t)\right)$$

$$F_m(t) = \sqrt{2b}v_m(t) + b\dot{x}_m(t) = \sqrt{2b}v_s(t - T_2) + b\dot{x}_m(t)$$

$$= F_m(t - T_2) - b\dot{x}_s(t - T_2) + b\dot{x}_m(t)$$

$$= F_s(t - T_2) + b\left(\dot{x}_m(t) - \dot{x}_s(t - T_2)\right)$$

In summary, we have

$$\dot{x}_s(t) = \dot{x}_m(t - T_1) + \frac{1}{b}\left(F_m(t - T_1) - F_s(t)\right) \tag{4.11}$$

$$F_m(t) = F_s(t - T_2) + b\left(\dot{x}_m(t) - \dot{x}_s(t - T_2)\right) \tag{4.12}$$

These equations show that the slave velocity will not track the master velocity exactly, and neither does the master force track that of the slave. But if both the velocities and the forces become constant, they will track each other.

For a closer look, equation (4.11) shows that, if the characteristic impedance $b$ is chosen very large, slave velocity can follow that of the master. But the force transparency cannot be

achieved according to equation (4.12). On the other hand, if small characteristic impedance is chosen, there will be a big difference between master and slave velocities. But master force can track the slave force quite well.

For small $b$, the communication impedance is small, the operator feels soft and easy to move, while for large $b$, the communication impedance is large and the operator feels it is hard to move. Therefore, ideally, small b is preferred for easy maneuver of the operator. But the velocity tracking can not achieved.

The error between the master and slave position can be represented as

$$\Delta \dot{x}(t) = \dot{x}_m(t) - \dot{x}_s(t)$$
$$= \frac{1}{\sqrt{2b}} \left[ \left( u_m(t) - v_m(t) \right) - \left( u_s(t) - v_s(t) \right) \right] \tag{4.13}$$

considering the time delay effect, we have

$$\Delta \dot{x} = \frac{1}{\sqrt{2b}} \left[ \left( u_m(t) - u_m(t - T_{d1}) \right) + \left( v_s(t) - v_s(t - T_{d2}) \right) \right] \tag{4.14}$$

apparently, for steady state, the velocity error becomes zero. And the position error is

$$\Delta x = \frac{1}{\sqrt{2b}} \int \left[ \left( u_m(\tau) - v_s(\tau - T_{d2}) \right) - \left( u_m(\tau - T_{d1}) - v_s(\tau) \right) \right] dt \tag{4.15}$$

Different configuration of the wave based teleoperation were discussed in [25], to account for the so called wave reflection.

Accordingly, conclusion can be drawn that, based on wave transformation, velocity/position transparency and force transparency could not be accomplished simultaneously.

For the case of zero delay, from equation (4.11) and (4.12), $T_1$ and $T_2$ will be zeros. The equations become, we will have the relations

$$F_m(t) = F_s(t) \qquad (4.16)$$

$$\dot{x}_m(t) = \dot{x}_s(t) \qquad (4.17)$$

This means, for zero time delay, the wave-based teleoperation will be degraded to the regular direct teleoperation without time delay.

## 4.2 Problems Caused by Varying Time Delay

For teleoperation system with varying time delay equation (4.10) becomes

$$P = \dot{x}_m^T(t)F_m(t) - \dot{x}_s^T(t)F_s(t)$$

$$= \frac{1}{2}\left(u_m^T(t)u_m(t) - v_m^T(t)v_m(t)\right) - \frac{1}{2}\left(u_s^T(t)u_s(t) - v_s^T(t)v_s(t)\right)$$

$$= \frac{1}{2}u_m^T(t)u_m(t) - \frac{1}{2}v_s^T(t - T_2(t))v_s(t - T_2(t))$$

$$- \frac{1}{2}u_m^T(t - T_1(t))u_m(t - T_1(t)) + \frac{1}{2}v_s^T(t)v_s(t) \qquad (4.18)$$

$$= \frac{d}{dt}\left[\int_{-T_1(t)}\frac{1}{2}u_m^T(\tau)u_m(\tau)d\tau + \int_{-T_2(t)}\frac{1}{2}v_s^T(\tau)v_s(\tau)d\tau\right]$$

$$- \frac{1}{2}u_m^T(t - T_1(t))u_m(t - T_1(t))\frac{dT_1(t)}{dt}$$

$$- \frac{1}{2}v_s^T(t - T_2(t))v_s(t - T_2(t))\frac{dT_2(t)}{dt}$$

Apparently, from equation (4.18), for the system to be passive, the condition

$$\frac{1}{2}u_m^T(t - T_1(t))u_m(t - T_1(t))\frac{dT_1(t)}{dt}$$

$$+ \frac{1}{2}v_s^T(t - T_2(t))v_s(t - T_2(t))\frac{dT_2(t)}{dt} \leq 0 \qquad (4.19)$$

has to be satisfied. If the time delays of both forward and return channels are increasing, equation (4.19) is not satisfied and thus the system is not passive. This means, for communication channels with varying time delay, wave transformation does not guarantee passivity anymore. And from equation (4.15), the position error between the master and the slave will be large since the wave signal will be distorted because of the variable time delay.

# CHAPTER 5 NETWORK COMMUNICATIONS

The Internet can be considered as a strongly connected network of computers, communicating with each other using packet-switched protocols[51, 52]. Currently, communications through the Internet use either Transport Control Protocol (TCP/IP), or the User Datagram Protocol (UDP). TCP provides a point-to-point channel for applications that requires reliable communication. It is a higher-level protocol that manages to robustly string together data packets, sorting them and retransmitting them as necessary to reliably transmit data. Furthermore, TCP/IP is a confirming based protocol, that means it transmits data packets and waits for the confirmation from the receiver. If no confirmation is received, it keeps resending the data packets. Thus, with TCP/IP, there is no data loss. Since the packet exchanges in the Internet are affected by the packets routes and handling policies at each node they traverse, the communication time delay is a random variable[15, 16]. For TCP/IP, the sending and receiving confirmations cause huge amount of time delay, and the data packets sent at different time may arrive at the same time, cause a shock wave like data flow at the receiver side. The waveform of the data series cannot be maintained either with TCP/IP. All these reasons make TCP/IP not a proper Internet protocol for real-time control. Our experience with the haptics enhanced vehicle simulation has proved this. When TCP/IP was used for data exchange, instability occurred in the steering wheel control.

On the other hand, UDP protocol provides network communications that are not confirmation based. Unlike TCP/IP, data packets delivered using UDP are not guaranteed to

be transmitted to the receivers. UDP sends independent packets of data, called Datagrams, from the sender to the receiver. Data are packed, addressed and then sent out, without getting confirmation from the receiver. The advantage of the UDP protocol is that it does not incur more time delay by waiting for the confirmation from the receiver. The disadvantage is, the data packets could get lost. The arrival order of the data packets is not guaranteed either. But since the waiting period is eliminated, the waveform of the data series can be better kept. Considering that the performance of a teleoperation system is inverse proportional to the length of time delay, UDP is a better choice for Internet based teleoperation.

Suppose there is no data packet loss, the sent and received signal can be conceptually shown in Figure 5.1
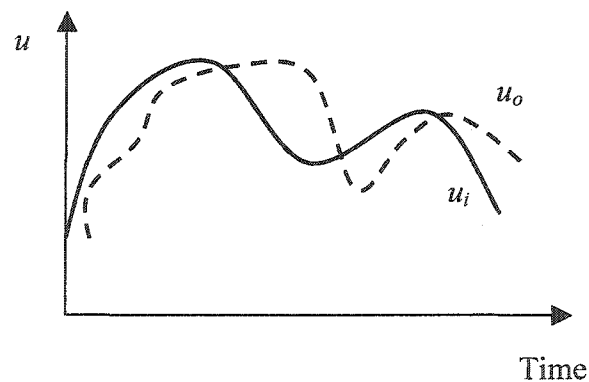


Figure 5.1 Waveform distortions due to the varying time

The time varying delay in the Internet communication not only cause stability problem in teleoperation, the traditional stabilization and teleoperation control scheme cannot control this kind of system very well because of the poor signal following performance.

# CHAPTER 6 PASSIVITY CONTROL OF TELEOPERATIONS

## 6.1 Passivity Control of Teleoperations

A complete teleoperation system can be represented using the block diagram in Figure 6.1. This representation is also analogous to the network from which the passivity concept was originated.
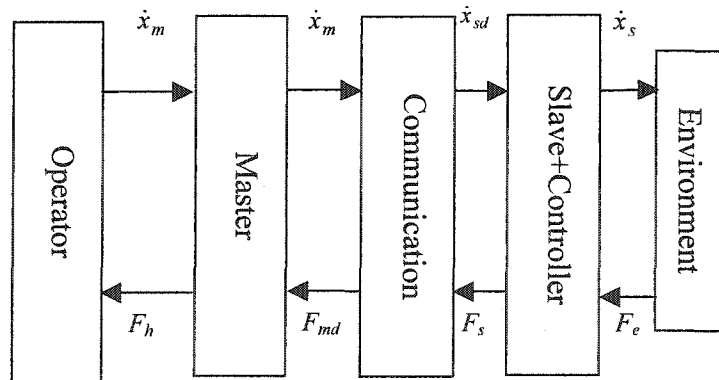


Figure 6.1  Block diagram of a teleoperation system

From Figure 6.1, the teleoperation system is comprised of a series of two-port or one-port network elements connected in cascade.

It has been shown that[25, 42] cascading of two port elements retains passivity if all the individual elements are passive. In a typical teleoperation system, excluding the operator, which is the power source, all the elements are passive except the communication channel.

The ideal communication channels do not have any time delay, thus we always have

$$\dot{x}_{sd} = \dot{x}_m$$
$$F_{md} = F_s$$

(6.1)

And from the definition of passivity, the ideal communication channel is lossless. The wave-based teleoperation[19, 25] uses wave transformation on the power variables before they are transmitted, which keeps the lossless property of un-delayed communication under the influence of the time delay.

From the configuration of teleoperation systems, the position/velocity command is sent from the master to the slave. The master is the leader and the slave is the follower. That means the energy should flow from the master to the slave. In an ideal communication channel, the energy enters the communication channel from the master side and exits the communication channel on the slave side at the same time and with the same amount. Without considering backdrivability, we assume the net energy can only transmitted from the master to the slave, and can never go the other way. This assumption is reasonable since for free motion, energy is provided by the human operator to the slave through master and the communication channel. The energy is either dissipated by the damping in master and slave or is stored by the two manipulators in the form of kinetic energy and elastic potential energy in the environment. There will be cases in which the stored energy being released and fed back to the master, but the released energy can never exceed the amount of energy the slave and environment have received from the master.

Actually, when one part of the system is isolated from the original teleoperation system, as shown in Figure 6.2, it becomes a one-port network element. Since the controlled slave and the environment are all passive and assuming ideal communication channel, we have, for the communication channel

$$\int_0^t \left( \dot{x}_m F_{md} - \dot{x}_{sd} F_s \right) d\tau = 0 \qquad (6.2)$$

for the controlled slave

$$\int_0^t \left( \dot{x}_{sd} F_s - \dot{x}_s F_e \right) d\tau > 0 \qquad (6.3)$$

and then for the environment

$$\int_0^t \dot{x}_s F_e d\tau \geq 0 \qquad (6.4)$$

The overall energy transfer on the network shown in Figure 6.2 is merely the sum of equation 6.2 – 6.4, that is

$$
\begin{aligned}
&\int_0^t \left( \dot{x}_m F_{md} - \dot{x}_{sd} F_s \right) d\tau \\
&+ \int_0^t \left( \dot{x}_{sd} F_s - \dot{x}_s F_e \right) d\tau \\
&+ \int_0^t \dot{x}_s F_e d\tau \geq 0
\end{aligned}
\qquad (6.5)
$$

collecting the terms, the equation becomes

$$\int_0^t \dot{x}_m F_{md} d\tau \geq 0 \qquad (6.6)$$
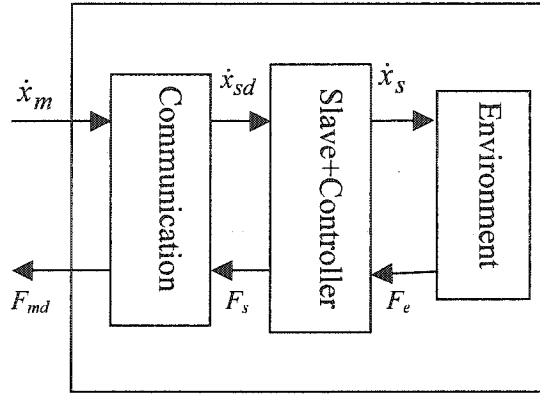


Figure 6.2 The one port equivalent of the right side system

Equation (6.6) means that the one port network element comprised of the communication channel, the slave and the environment can only dissipate energy and never generate energy. From the passivity condition of one port network, the assumption implies that the combined one port element should be passive all the time. This is the starting point of our method.

The only component that may cause instability in Figure 6.2 is the communication channel due to time delay. The ideal case is to monitor the energy entering the two-port component, and force equation (6.2) to be true all the time. This scheme has been used in the control of haptic interfaces by Hannaford and Ryu[42]. But for teleoperation systems, since there exist time delays and the information at the two sides of the communication channel cannot be accessed in real time, monitoring both sides is not applicable. Based on the

discussion at the beginning of this section, the net energy can only transmitted from the master to the slave, and can never go the other way. We can instead monitor the total energy entering the system shown in Figure 6.2, and if passivity is lost, a passivity regulator should be employed to reinstate passivity. In the next section, the details of the passivity regulator design will be discussed.

In practical control problems, the control systems are implemented digitally, thus discretization is inevitable. It has been shown [46, 48, 53]that the discretization, via sample and hold, of a passive system is in general, not passive. The typical example is robot hard surface contact control. It is well known that when the robot manipulate on a hard surface, instability can occur. But still, if the energy exchange in the one-port network shown in Figure 6.2 is monitored and regulated, passivity will be maintained, no matter what had caused the loss of passivity.

## 6.2 Passivity Regulator

In our method, a passivity regulator is put at the master side of the communication channel. When the system loses passivity, the regulator is activated to recover passivity.

Note that, in discrete time domain, equation (3.20) becomes

$$\sum_{i=1}^{n} \left[ \dot{x}_1^T(i)F_1(i) + \dot{x}_2^T(i)F_2(i) + \cdots + \dot{x}_k^T(i)F_k(i) \right] \Delta T \geq 0 \tag{6.7}$$

where $\Delta T$ is the sampling rate of the system, $k$ is the number of the open ends of the network. Hannaford and Ryu[42] named the left side of equation (6.7) as passivity observer (PO) $E_{obsv}(n)$, means the sign of $E_{obsv}(n)$ tells the passivity of the system. When $E_{obsv}(n)$ is greater than zero all the time, the whole system dissipates energy, and if at any instance $E_{obsv}(n)$ falls below zero, the system generates energy, and the excessive energy generated by the system is $-E_{obsv}(n)$. By knowing the amount of energy the system generated, a passivity regulator can be applied to dissipate the exact amount of the excessive energy and maintain the passivity of the system.

The relation of the passivity observer and the power variables is

$$E_{obsv}(n+1) = E_{obsv}(n) + \dot{x}_m F_{md} \Delta T \qquad (6.8)$$

If $E_{obsv}$ is greater than zero all the time no action needs to be taken because the system is stable. When $E_{obsv}$ becomes negative, the system starts to generate energy, and the excessive energy generated by the communication channel needs to be dissipated in order to stabilize the system. It is important to note that the contact force is always in the negative direction (if the initial velocity of the manipulator before the contact is specified as positive, and the contact force always pushes the manipulator away from the environment). Contact force can only does work on the manipulator when the manipulator velocity is in the negative direction too, that is when $Fv>0$. That means, $E_{obsv}$ can only go negative when the manipulator is being bounced back.

From equation (6.8), there are two ways to keep $E_{obsv}$ nonnegative. The first method is to change the command velocity going into the communication channel, and the other method is

to change the desired force of the master manipulator. When the first method is used, the feedback force is being used unchanged, and the command velocity transmitted to the slave is changed to keep $E_{obsv}$ from going negative. The actual value of the command velocity can be represented as

$$\dot{x}_m = -\frac{E_{obsv}(n)}{F_{md}\Delta T} \tag{6.9}$$

or just simply make the command velocity zero.

When the master velocity is transmitted unchanged, to maintain passivity of the one-port network, the feedback force has to be changed. The easiest way to dissipate the extra energy is to make $F_{md}=0$ when equation (6.8) becomes negative, so the excessive energy will be eliminated without being passed onto the master. To be more accurate and less conservative, the regulated master desired force can be calculated as

$$F_{md} = -\frac{E_{obsv}(n)}{\dot{x}_m\Delta T} \tag{6.10}$$

From both equation (6.9) and equation (6.10), the sampling period is in the denominator of the expressions. When the sampling period is small, numerical instability may occur because of the division by a small number. In order to avoid numerical instability, for constant sampling period, divide equation (6.8) with $\Delta T$ and we have the relation

$$E_{obsv}(n+1)/\Delta T = E_{obsv}(n)/\Delta T + \dot{x}_m F_{md} \qquad (6.11)$$

which can be reformulated as

$$P_{obsv}(n+1) = P_{obsv}(n) + \dot{x}_m F_{md} \qquad (6.12)$$

From equation (6.12), for constant sampling rate, passivity observer can be represented by the power injected to the one-port network. Note that equation (6.12) is derived from equation (6.8). It has the same physical meaning as equation (6.8), except it has stricter constraint of constant sampling rate.

Based on equation (6.12), equation (6.9) and equation (6.10) can be rewritten as

$$\dot{x}_m = -\frac{P_{obsv}(n)}{F_{md}} \qquad (6.13)$$

$$F_{md} = -\frac{P_{obsv}(n)}{\dot{x}_m} \qquad (6.14)$$

For the passivity regulation scheme in equation (6.13), the position/velocity following will be compromised to maintain passivity. When system passivity is lost, the slave will not follow the master velocity. Especially when the master is being bounced back by $F_m$, to keep the system from going impassive, the slave velocity command will be kept low or even zero. The result will be that $F_m$ will keep high and the master will be pushed back further.

Negative force combined with negative master velocity will still render the system impassive. Since the feedback force is not being changed, the energy flow from the one-port network to the master is not really being changed either. That means the excessive energy is not being dissipated. And the overall energy in the system can still accumulate and destabilize the system. The problem of this method is that, although the command velocity transmitted to the slave is changed, the actually master velocity cannot be changed. Changing the input to the one-port network cannot change the passivity of it

On the other hand, when the feedback force is modified to maintain passivity as shown in equation (6.14), the output of the one-port network is changed. It is equivalent to adding an energy dissipative component to the network and dissipating the excessive energy. This method is more physical intuitive and can effectively change the passivity of the system

Besides the scheme shown in equation (14), a simpler way to keep the system passive is to force $Fm$ to be zero when passivity is lost. Although equation (14) should give more accurate and less conservative result, simulations show that there are no significant differences in the system responses using these two schemes. Note that low velocity may pose a problem on equation (6.14). But since when master velocity is small, the energy changes will be small too, and our experiences show that (6.14) does not bring problems.

In next section, simulations are shown to test the effectiveness of the proposed method.

## 6.3 Simulation of The Passivity Regulation

Simulations were performed to verify the effectiveness of the method. For the first case, the second passive regulator expressed by equation (6.9) is used. The mass of the master is *1 kg*, the damping rate is *1 Ns/m.* and the mass of the slave is *2 kg*, while the damping rate is same at *1 Ns/m*. The PD controller has the parameters of $K_p$ = *200* and $K_d$ = *5*. The environment is modeled as a stiff surface at the position $x$ = *8* m with a stiffness of *1000 N/m*. The time delays used are *0.5* second both ways.

Figure 6.3 shows the position tracking of the slave. It shows that the slave follows the motion of the master with a 0.5 second delay. Finally, the slave was constrained at the position of 8 m because of the stiff environment. Note that, before the contact between the slave and the environment, there is a bounce happens, this is due to the feedback of the coordinating force. Although no contact is involved, large coordinating force hinders the free motion of the master. After the initial contact, the manipulators bounce a couple time and then converge to steady state. Note that, after the transient response, the master steadily but slowly approaches the position of the slave.

Figure 6.4 shows the tracking of master force to the slave force. The master force is not continuous because of the passivity regulation. It was lowered when the system become non-passive. For the other parts of the trajectory, the master force can track the slave force after the communication delay. Figure 6.5 shows the energy entered the communication channel. Again, under the passive regulation, the energy is always nonnegative, and thus the passivity is reserved.
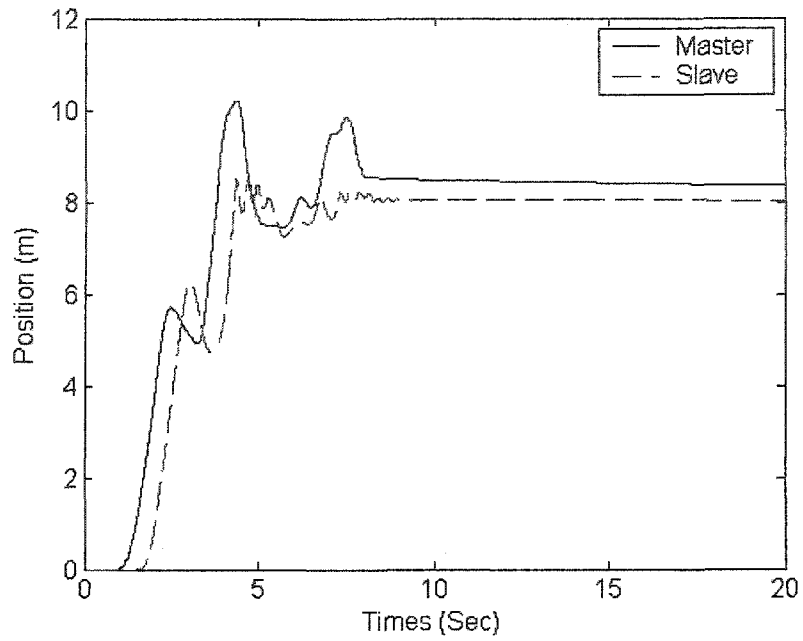
Figure 6.3  Master and slave positions
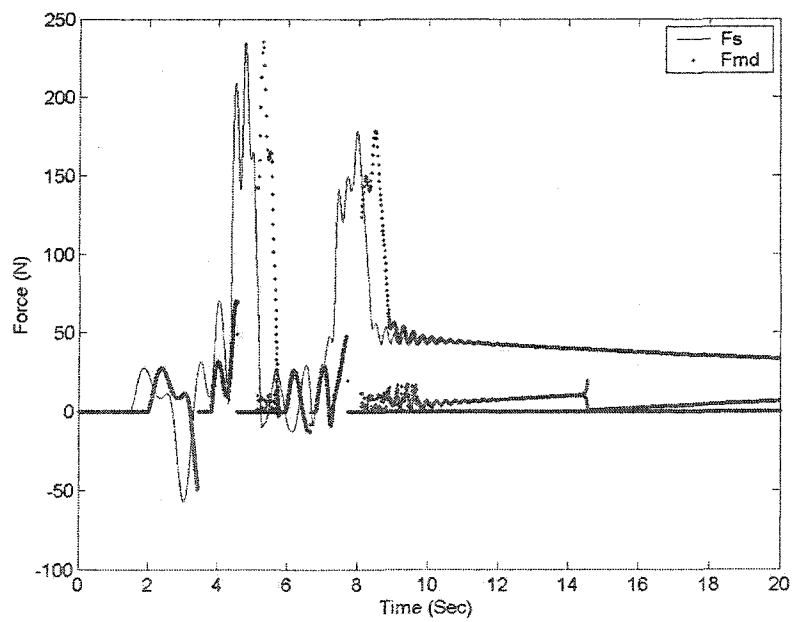


Figure 6.4  Master and slave forces
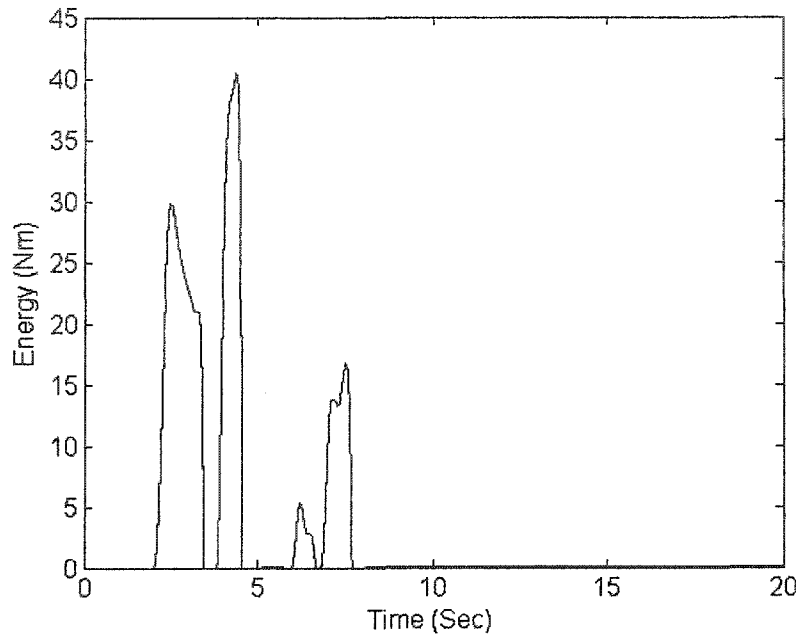
Figure 6.5 The regulated energy entering the communication channel

As a comparison, Figures 6.6 and 6.7 show the response of the same system without passivity
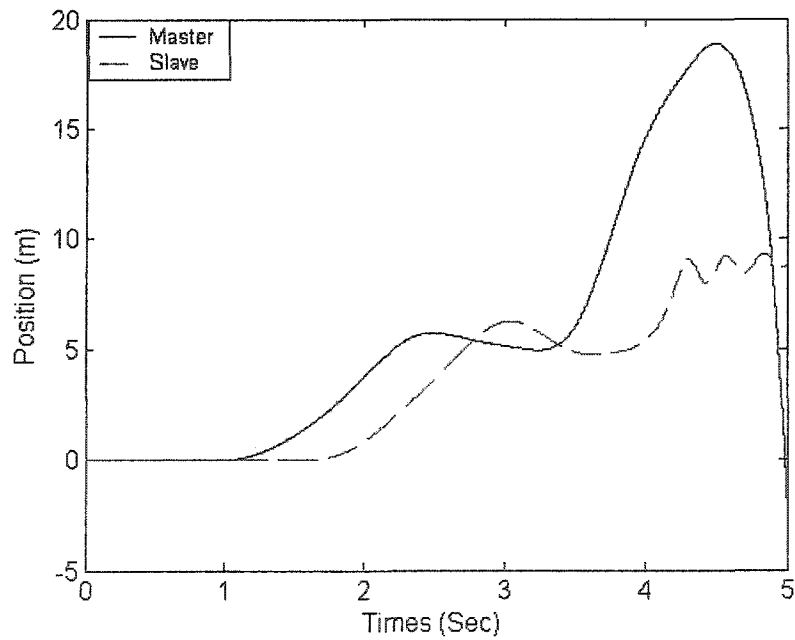
regulation.



Figure 6.6 Master and slave positions without passivity regulation
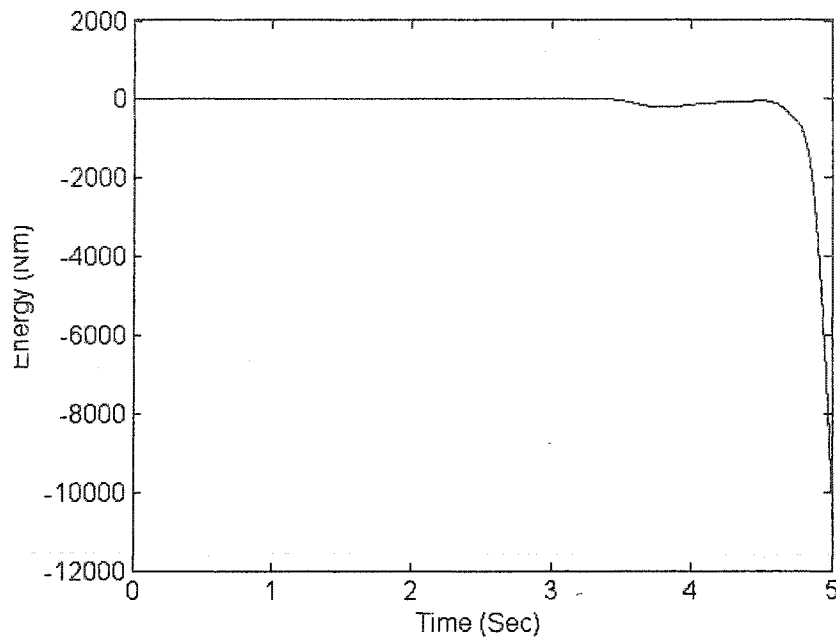
Figure 6.7 The unregulated energy entering the communication channel

Figure 6.6. shows that the system diverges in less than 5 second. Figure 6.7 shows that the energy entering the system became negative, this means the system generates energy, which is the direct reason for system instability.

Figure 6.8-11 show the response of the same system but with forward time delay of 1 second, and the backward time delay of 0.5 second.
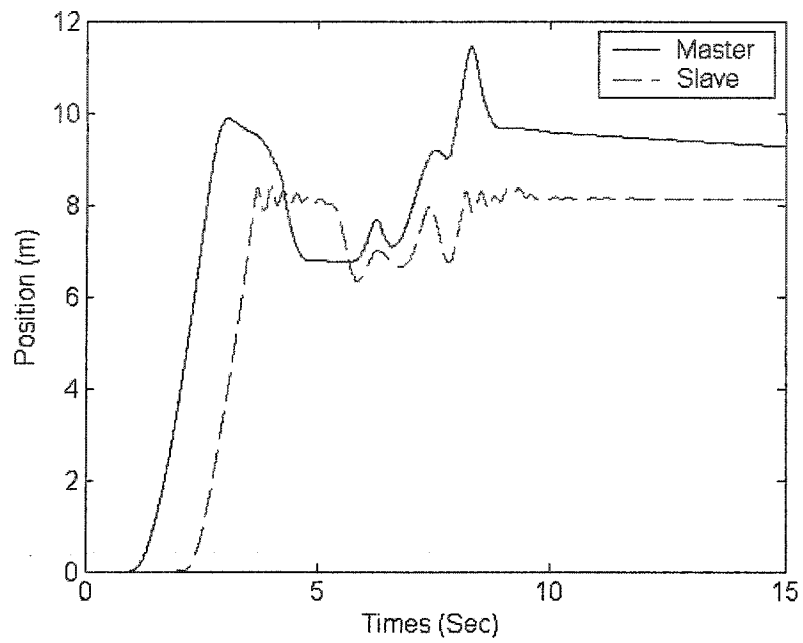
Figure 6.8  Master and slave positions with *T1 = 1 sec, T2 = 0.5 sec*
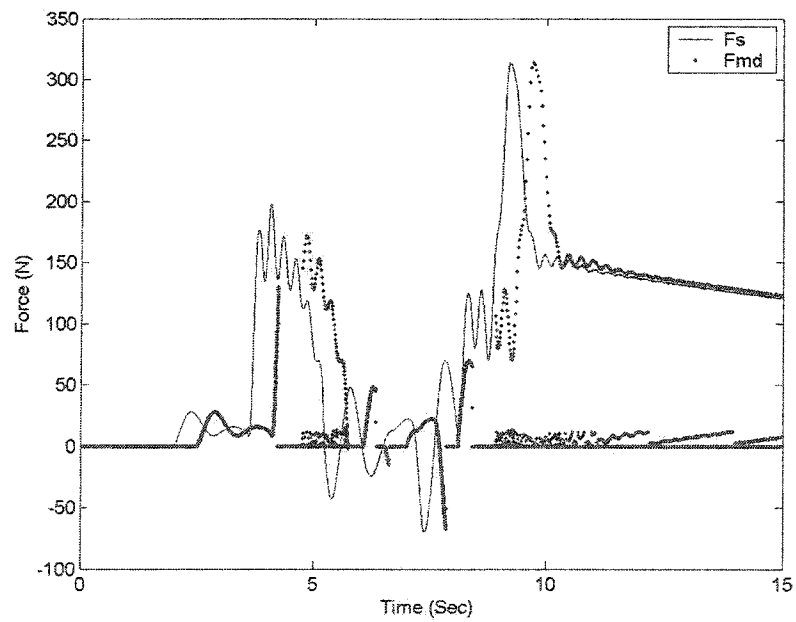


Figure 6.9  Master and slave forces with *T1 = 1 sec, T2 = 0.5 sec*
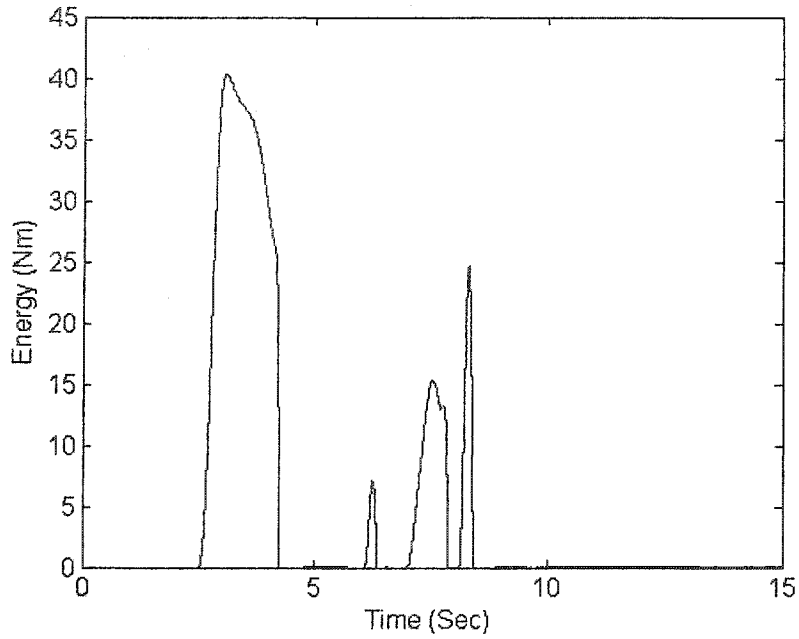
Figure 6.10 Regulated energy entering the communication channel with *T1 = 1 sec, T2 = 0.5 sec*

Figure 6.8 shows 1 second delay between the master and slave positions, while Figure 6.9

shows 0.5 second delay of force tracking which corresponds to the backward communication

delay. Again, Figure 6.10 shows that the energy entering the system was kept positive. This

case verified that the proposed control scheme is capable of stabilizing the teleoperation

system with different forward and backward time delay. And good position and force

tracking were also achieved. In fact, because our approach only observe and modify the

input and output of the one-port network, and does not require the internal information of the

network, time delays, as internal parameters of the network, do not affect the stabilizing

ability of the method. Of course, although time delays still affect the position and force

following performance, and larger delays certainly adversely affect the performance.

## 6.4 Discussion on Different Force Feedback Configurations

Hannaford and Anderson[10] proved that, when the environment contact force is fed back directly to the master, the system may be unstable even without time delay in the communication channel. And this is the reason why the coordinated force, instead of the contact force itself, is fed back to the master to avoid the possible instability. Because in simulation using numerical methods, and in the experiments involving discrete components (D/A, A/D and digital computer), the discretization of the contact force (equivalent to a spring force), makes the lossless spring not passive[46], when the environment is stiff, the contact becomes more impassive. This impassivity leads to the system instability. On the other hand, when the coordinated force is used as feedback, the operator will feel the force even when there is no contact happens. Because of the time delay, the feedback of the coordinated force may render the system unstable even during free motion. The two different configurations are shown in Figure 6.11 and Figure 6.12.
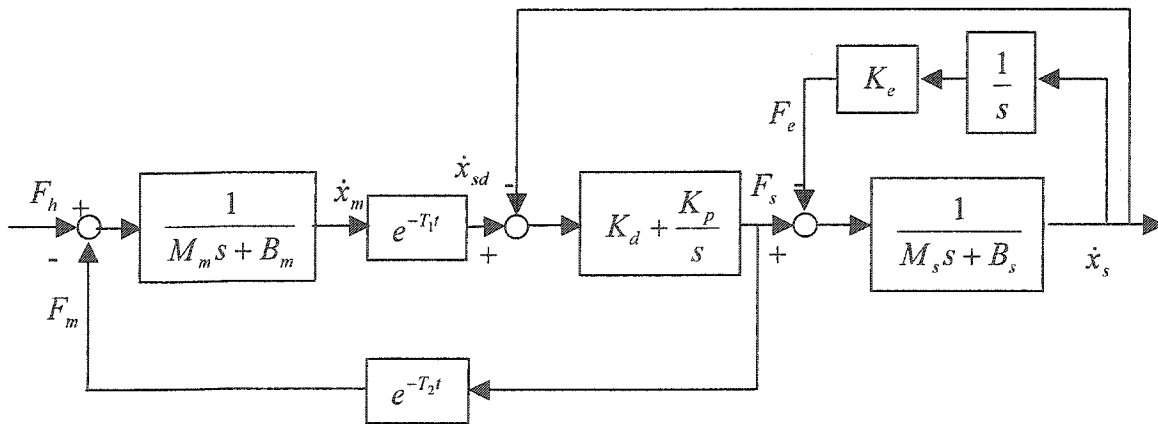


Figure 6.11 Teleoperation with coordinating force as feedback
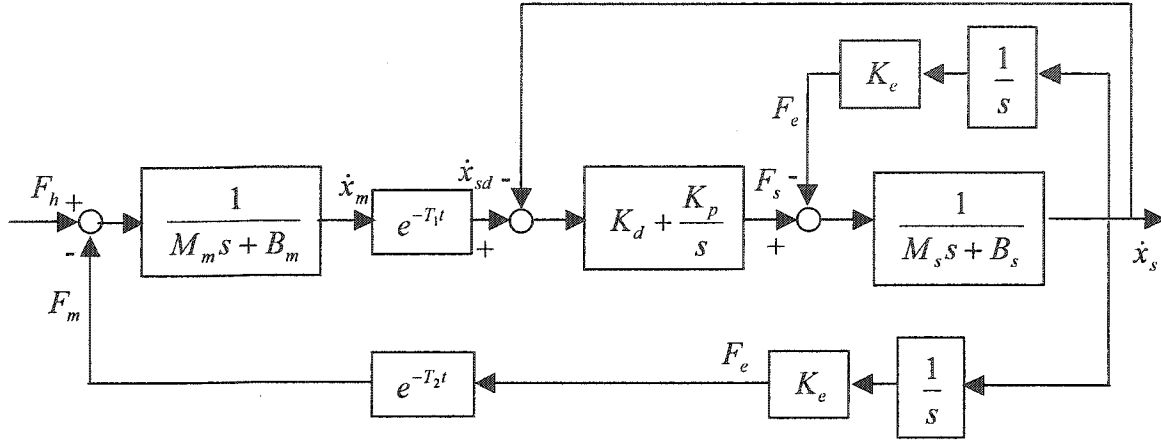
Figure 6.12 Teleoperation with environmental force as feedback

From Figure 6.11, when the coordinating force is fed back to the master manipulator, the master command force is nonzero whenever there is a difference between the delayed master motion and the actual slave motion, either position or velocity. Thus the impassivity of the communication channel will destabilize the teleoperation system even when there is no contact. While ideally, when there is no contact with the environment, the system is equivalent to a unilateral teleoperation system, and there should not be any stability issues.

Simulations were conducted to demonstrate the problems it may bring when using the coordinating force as feedback. In the simulation, a time delay of 0.5 second was used in both the forward and backward route of the communication channel. The other specifications are same as in the previous simulations.

The simulation of free motion teleoperation with $F_s$ as feedback is shown below. Figure 6.13 shows the position response. Figure 6.14 shows the velocity response. Figure 6.15

shows the force response, and Figure 6.16 shows the energy entering the communication channel. The plots show that the system is unstable even though there is no contact happens. From Figure 6.16, we can see the energy entering the communication channel goes to negative very quickly. The instability is again caused by the asynchronization of the velocity command and force feedback.
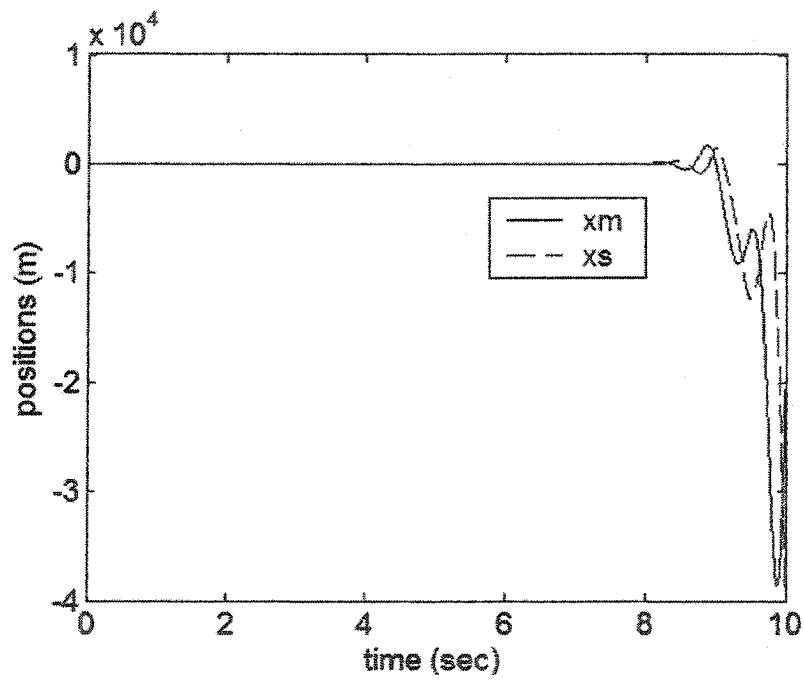


Figure 6.13 Master and slave position response for free motion with 0.1 s delay
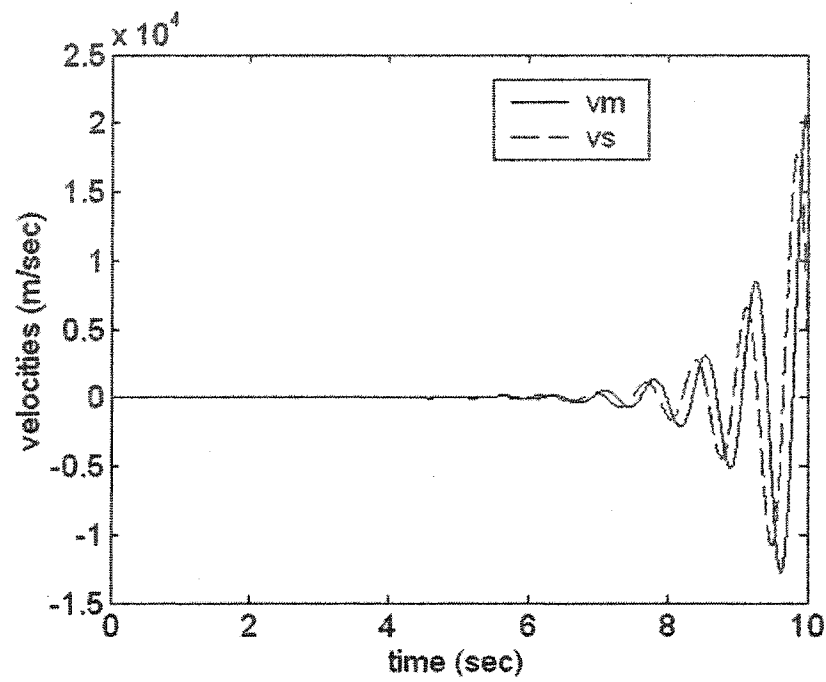
Figure 6.14  Master and slave velocity response for free motion with 0.1s delay
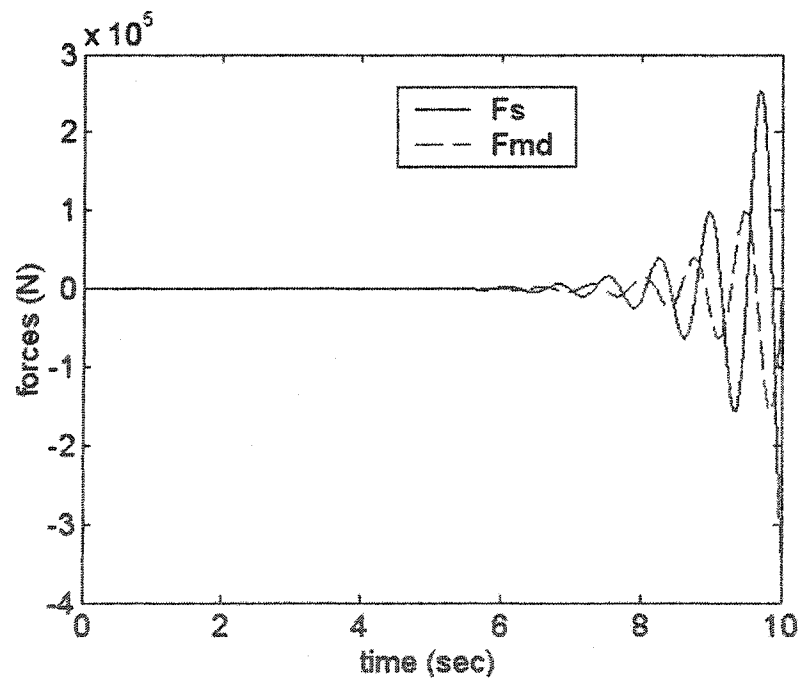


Figure 6.15  Master and slave force response for free motion with 0.1 s delay
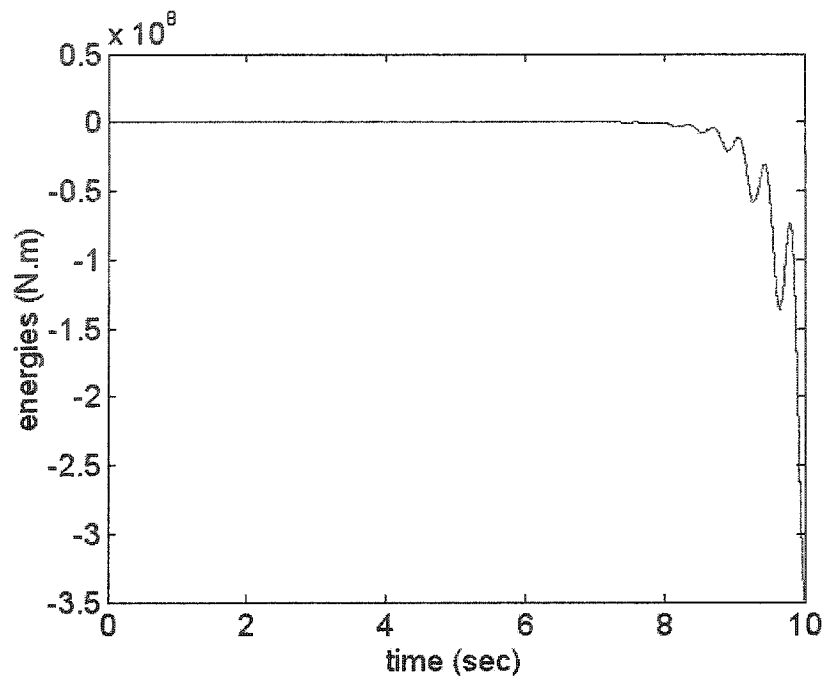
Figure 6.16 Energy entering the network for free motion with 0.1 s delay

As a comparison, the simulation of the system response with the contact force being fed back was also conducted, as shown in Figure 6. 17-19. For this case, since there is no contact, the force feedback from the slave to the master is always zero. This is equivalent to a unilateral teleoperation system. Since unilateral teleoperation systems don't have stability problem, the passivity regulator stays inactive. This means, during free motion, if contact force (environmental force) is used as feedback, the system will be automatically stable without any effort from the controller. Figure 6.19 shows the coordinating force and the master command force. In order to drive the slave to follow the motion of the master, significant coordinated force is generated, but since no contact happens between the slave and the environment, there is no force being sent back to the master. This results in zero energy exchange between the master and the communication channel. From the discussion

and the simulation, at least during free motion, a teleoperation system performs better when

contact force $F_e$ is used as the feedback instead of coordinating force $F_s$.
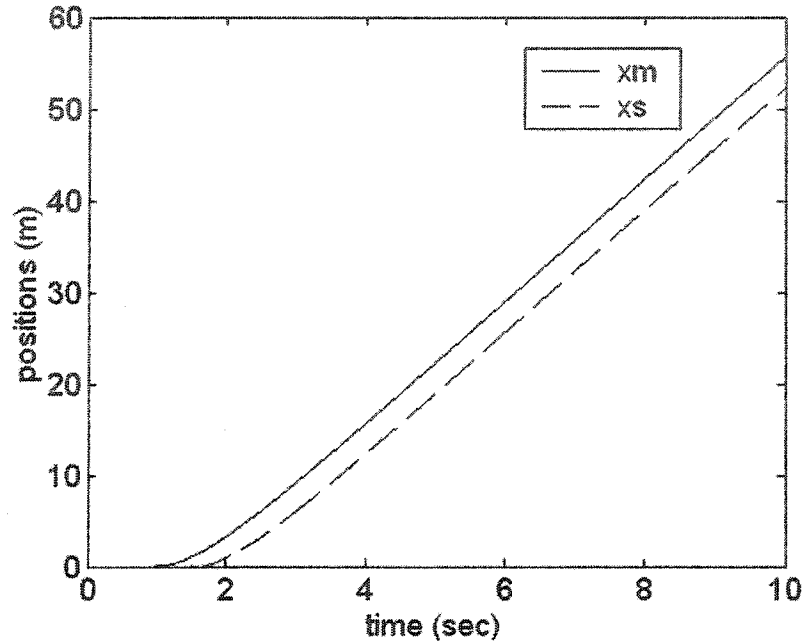


Figure 6.17  Master and slave position response for free motion with 0.1 s delay
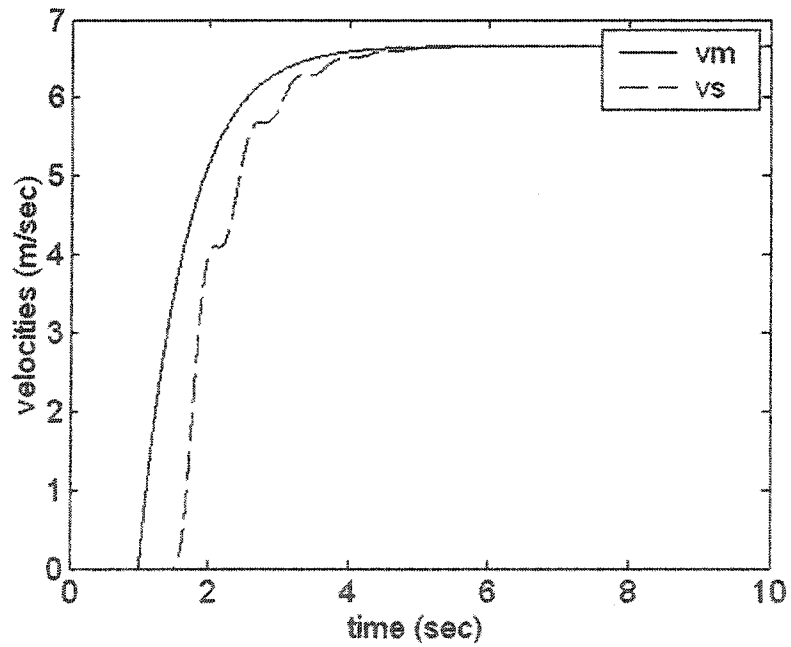


Figure 6.18  Master and slave velocity response for free motion with 0.1 s delay
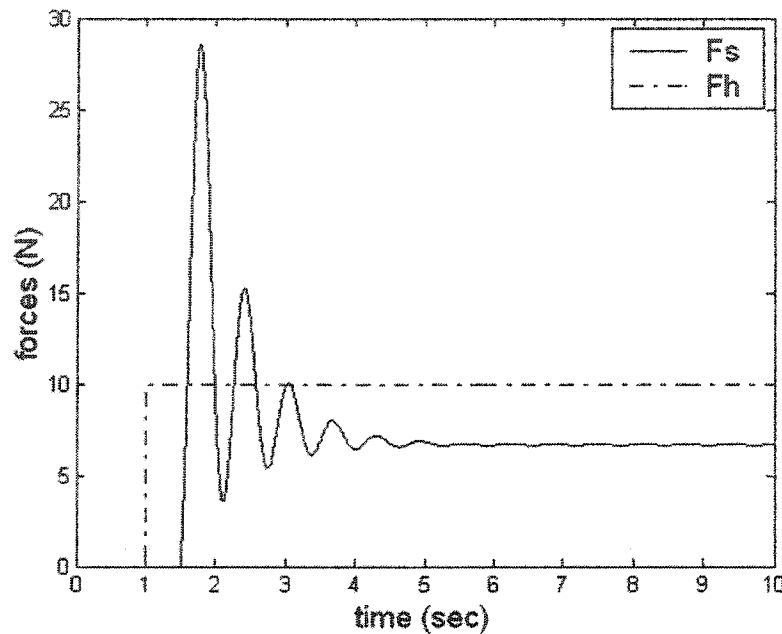
Figure 6.19 Master and slave force response for free motion with 0.1 s delay

Now that the system performance for free motion with the two different configurations has been discussed. It is worth the time to investigate when passivity based control scheme is applied, how the system will perform in free motion.

Figure 6.16 shows that when coordinating force is used as feedback to the master, the teleoperation system is not passive with time delays in the communication channel. If the passivity of the system is regulated using our passivity regulator, the system response will no longer go unbounded and passivity is maintained. But the feedback of the coordinating force keeps the master from free motion, and the constant tendency of going impassive and thus triggering passivity regulator results in oscillatory response, as shown in Figure 20-23.
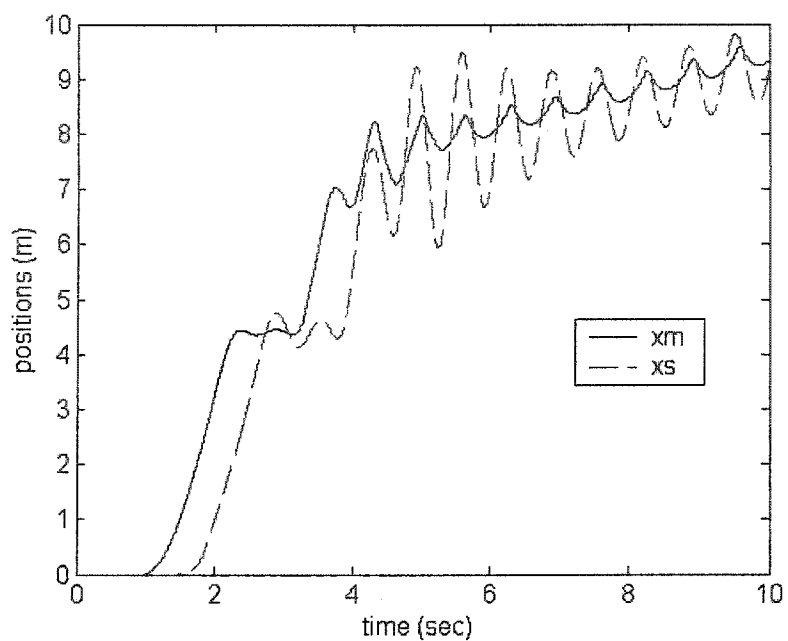
Figure 6.20 Passivity regularized position response for free motion with 0.1 sec delay
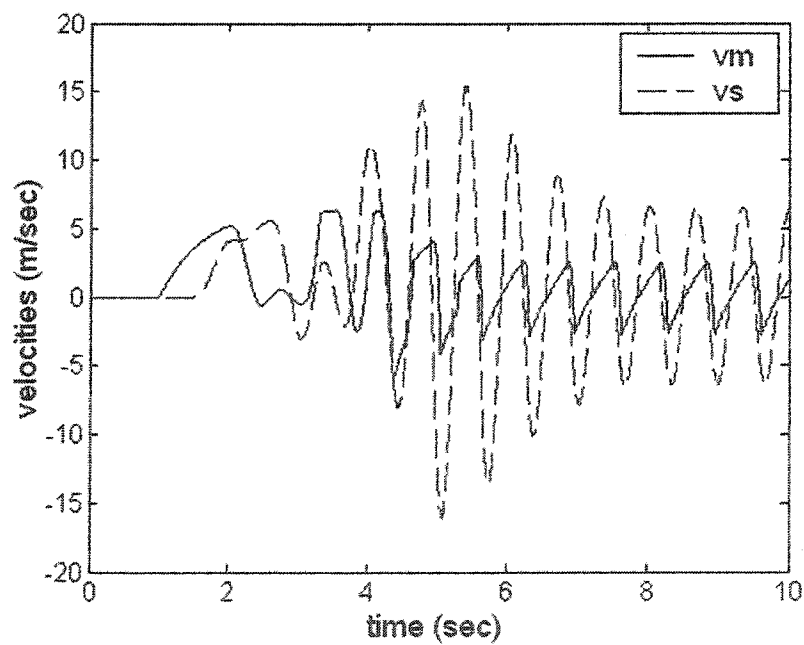


Figure 6.21 Passivity regularized velocity response for free motion with 0.1 sec delay
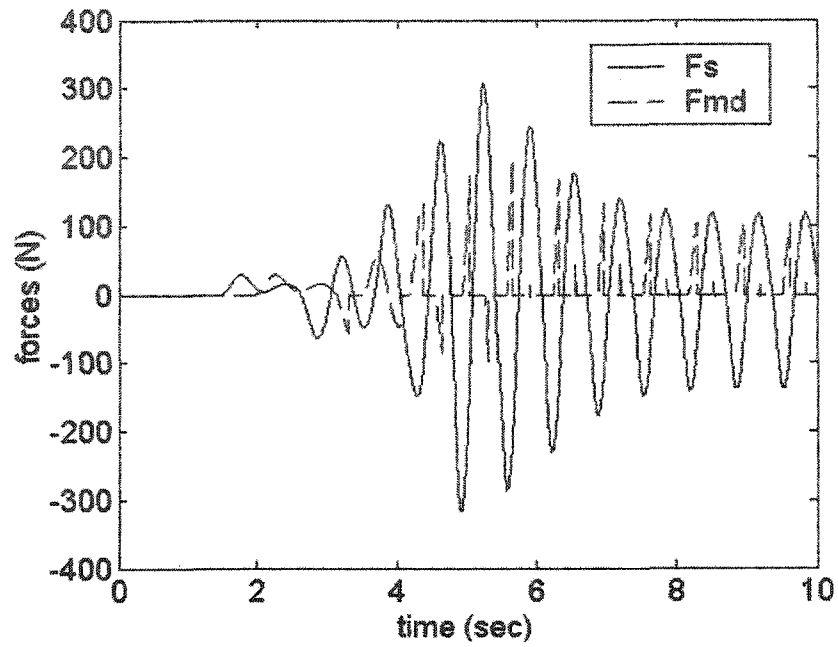
Figure 6.22 Passivity regularized force response for free motion with 0.1 sec delay,
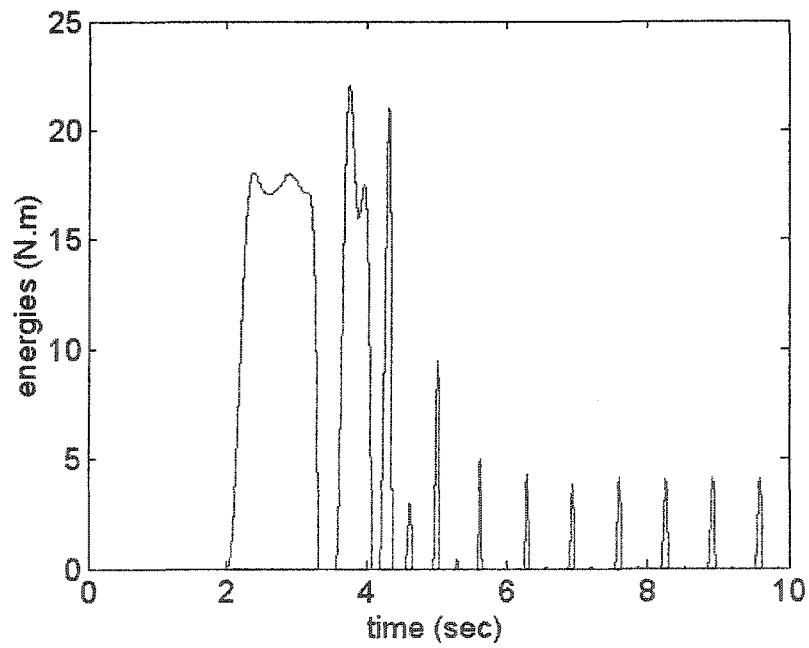


Figure 6.23 Passivity regularized energy response for free motion with 0.1 sec delay,

The main reason why researchers have used coordinating force instead of the contact force as feedback is that, for high stiffness environments, when the contact force is used for feedback, instability may occur even when there is no time delay in the communication channel[10]. The contact instability is caused by discretization of the elastic environment, because discretization using a limited sampling rate makes a spring impassive[48]. While it is true that the coordinating force converges to the contact force at steady state, it is not equal to the contact force in general. Especially in free motion, contact force is zero while coordinating force is usually not. As a result, when the coordinating force is used as feedback, the operator will not feel the real contact force. Instead, the operator will feel a force feedback even when there is no contact occurs. This impairs the performance of free motion and adversely affects the degree of transparency. The passivity regulation scheme developed in this work can prevent the teleoperation system from going impassive when contact happens. It makes it possible to use the contact force directly instead of coordinating force as feedback in teleoperations.

Figures 17-18 shows that, in free motions, for the configuration with contact force as feedback, the system is stable and has good motion following performance compared to those shown in Figure 13-14. Since our passivity regulator will maintain system passivity when contact happens, contact instability is not a concern anymore. This implies that using the contact forces as feedback may achieve better position and force following performance in bilateral teleoperations.

Figure 6.24-27 show the system response with $T_1=T_2=0.5$ second, $B_m=1.5$ Ns/m. In the simulations, passivity regulation is applied to maintain system passivity.
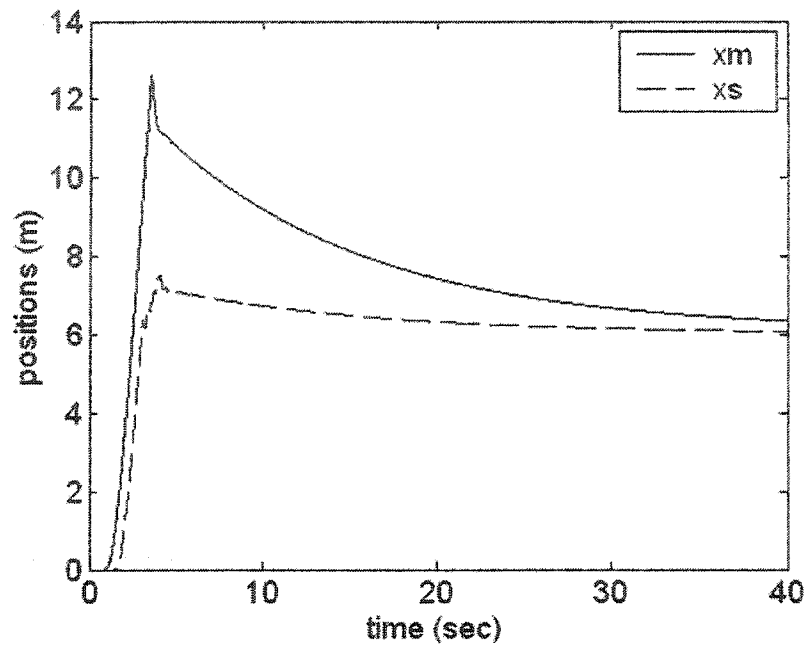
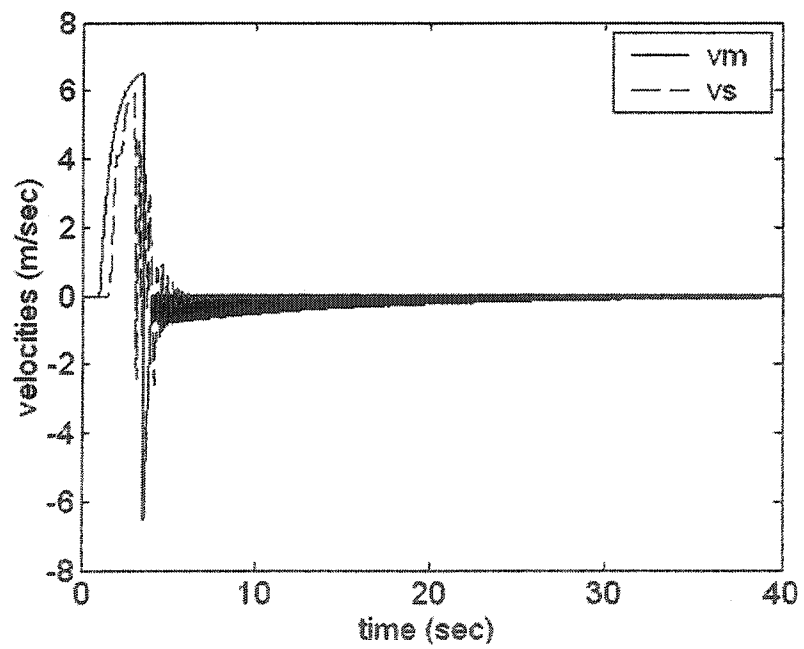Figure 6.24 Master and slave position response with 0.5 s delay



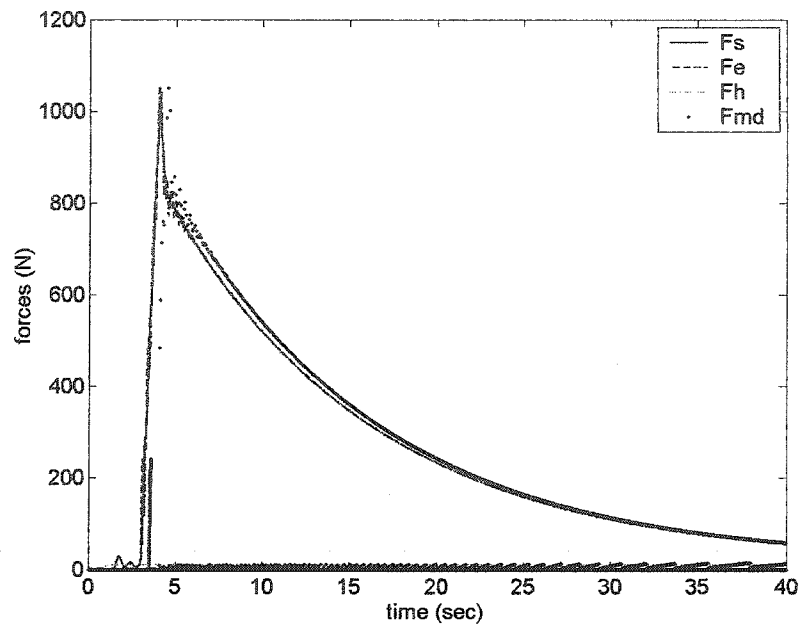Figure 6.25 Master and slave velocity response with 0.5 s delay

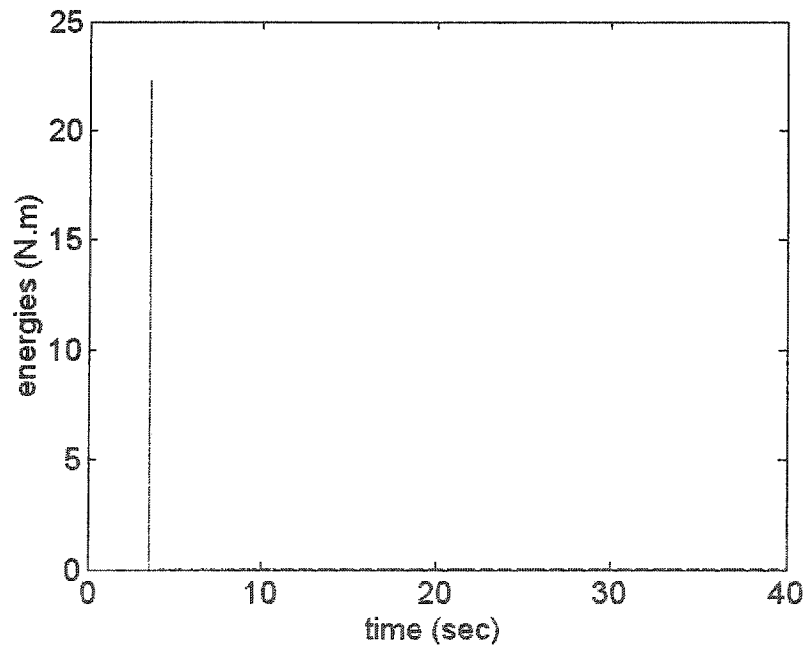Figure 6.26  Master and slave force response with 0.5 s delay



Figure 6.27  Energy response with 0.5 s delay

Compare the responses shown in Figure 6.24- 27 to those shown in Figure 6.3-5. It is easy to see that the position and force responses are much smoother, and there is no jittering during free motion. But it should be noted that there are bigger overshoots in the responses with contact force as feedback. This larger overshoots are because in free motion, there is no force feedback to keep the master from moving too fast. But in practical teleoperation, the human operator will control the velocity of the master instead of applying a constant force on it, thus the high overshoot will not happen when a human operator is manipulating the master.

## 6.5 Effect of System Damping on the Passivity Regulation

When the passivity regulator is triggered, it automatically dissipates the excessive energy that renders the one port system impassive by modifying the feedback force. But the passivity regulation only makes the system lossless, not strictly passive, and it is easy to imagine that for a master manipulator with low damping, the response will be highly oscillatory. Moreover, discretization of the master system has destabilizing effect too. If there are not enough damping at master side, the system response will not converge in a timely manner or the system may even be unstable even though the passivity regulator is applied..

To verify this, simulations were performed. Figure 6.28 – 31 show the responses with $T_1$ = $T_2$ = 0.5 second, and the damping coefficient of the master robot is $B_m$ = 0.02 N.s/m. The environment stiffness is $K_e$ = 700 N/m.
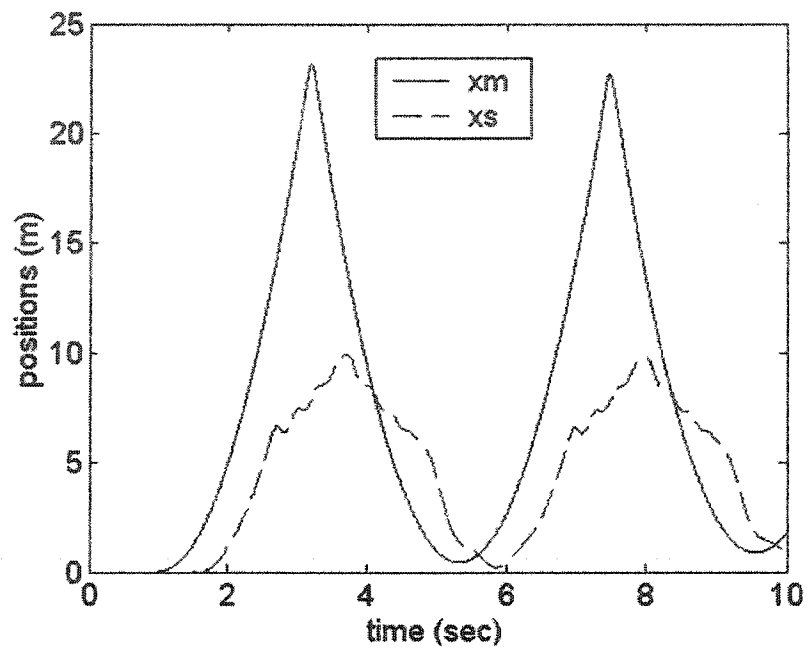
Figure 6.28 Master and slave position response with $B_m=0.02N.s/m$
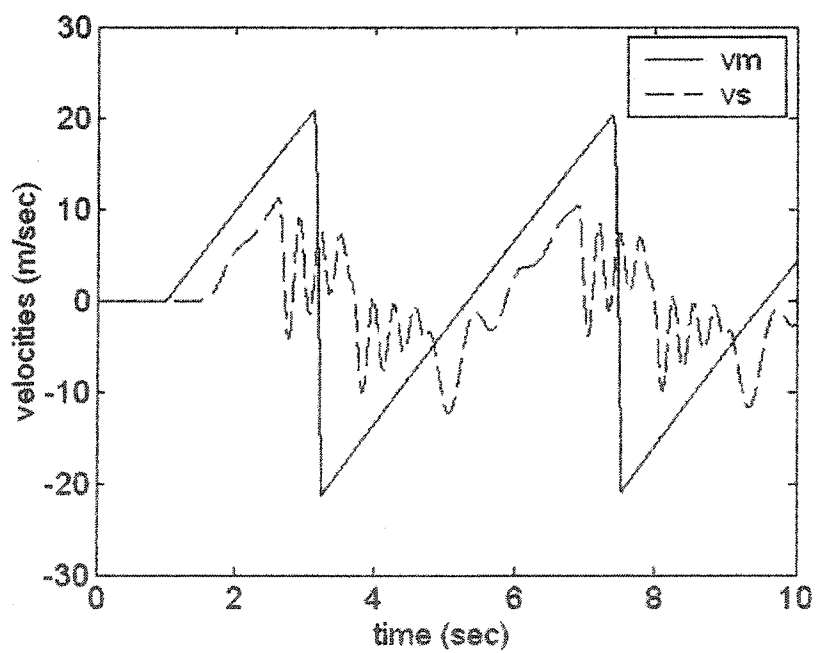


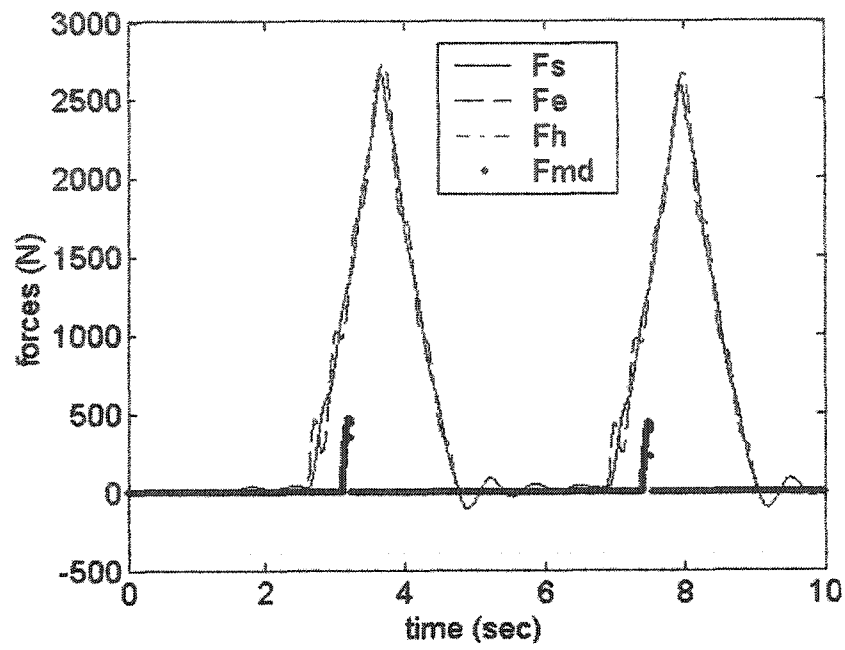Figure 6.29 Master and slave velocity response with $B_m=0.02N.s/m$
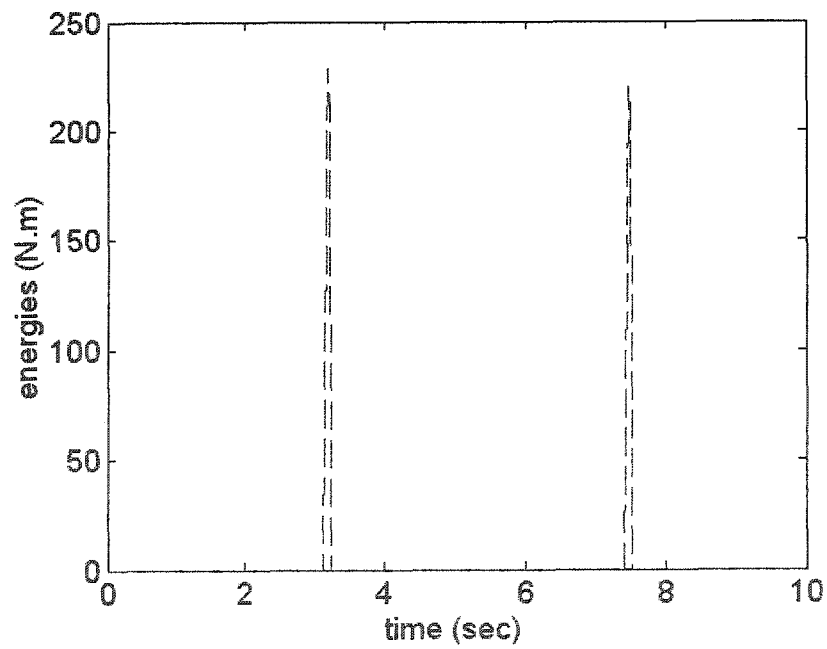
Figure 6.30  Force response with $B_m=0.02N.s/m$



Figure 6.31  Energies with $B_m=0.02N.s/m$

Figures 6.28-31 show that although the passivity regulator has been activated and the passivity of the one-port network has been maintained. The system responses cannot converge to the steady state in a short period of time. This is because the negligible damping cannot dissipate all the energy generated by the master due to discretization. In order to have satisfactory responses, more damping should be added at the master side. Figures 6.32-35 show the system responses with $B_m = 0.5$ $N.s/m$. Compared to the $B_m=0.02N.s/m$ case, the system responses converge to the steady state, but the damping is still not high enough for faster settling. The system responses for $B_m = 1.0$ $N.s/m$ are shown in Figure 6.24-27, and it can be seen that the oscillation is completely eliminated by the master damping. Another fact needs to be noted is that, with the increase of time delays, the overshoots in system responses increase too. This is easy to understand since it takes longer for the contact force to be transmitted to the master when longer time delays are involved.
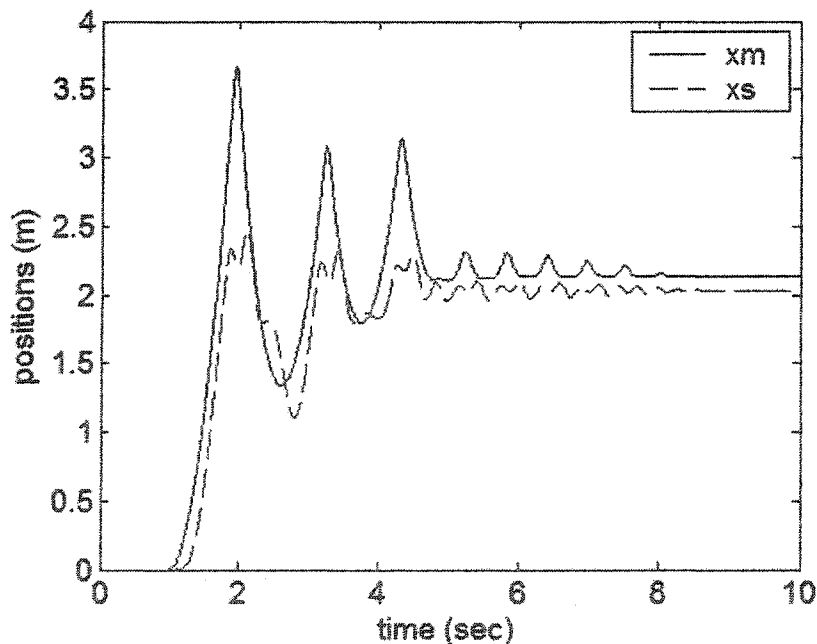


Figure 6.32 Master and slave position response with $B_m=0.5N.s/m$

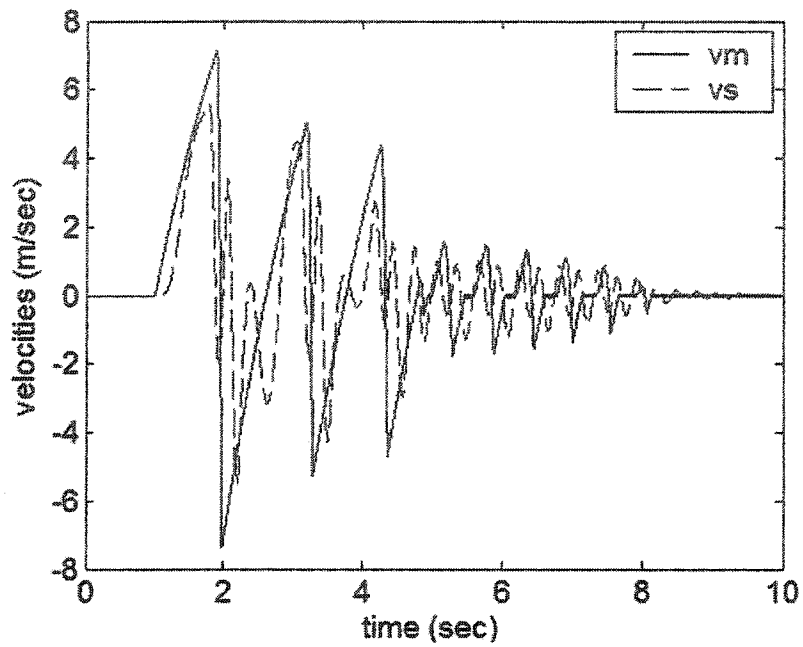Figure 6.33 Master and slave velocity response with $B_m=0.5N.s/m$
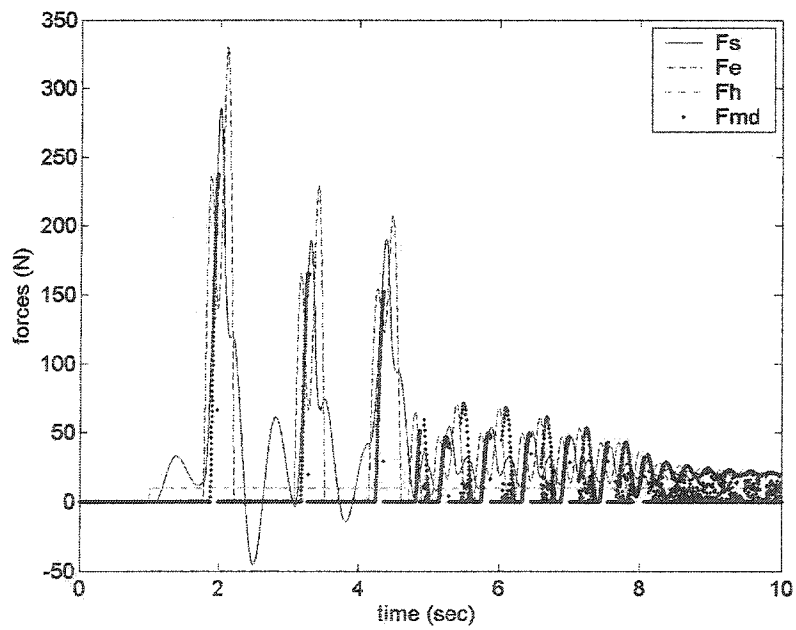


Figure 6.34 Master and slave force response with $B_m=0.5N.s/m$
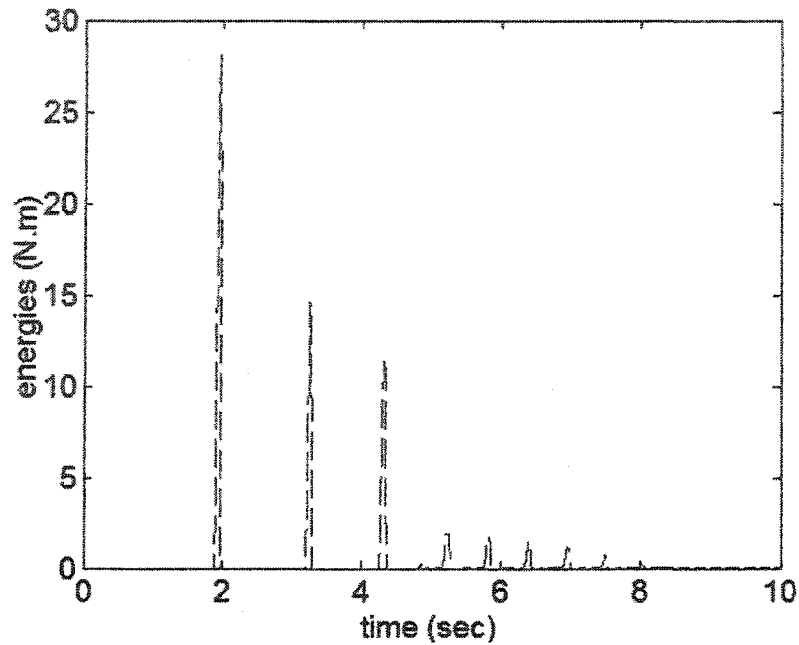
Figure 6.35  Energies with $B_m=0.5N.s/m$

## 6.5 The Advantage of Passivity Control Method

The passivity control scheme proposed in this work does not depend on the model of the local and remote systems. Neither does it rely on the knowledge of the remote environment model. It does not require information about the length of the time delay either. By merely monitoring the energy entering the communication channel, and triggering the passivity regulator when needed, this control scheme can stabilize the system with any time delays, including variable delays. This method is easy to understand and easy to implement. The

effectiveness of the method is verified by simulation. Compared with the wave-based control method, our method does not require the tuning of the characteristic impedance, it only interferes the operation of the system when instability occurs. This feature minimized the adverse effect on system tracking performance while keeping system passive. Wave-based method is believed to be too conservative and it achieves stability at the price of lowered performance[32, 42].

One limitation of this system is that in order to keep system passive, the force signal from the slave to the master is altered. The result of this is, when the passivity regulator is triggered, the operator will not feel the actual force applied on the slave. However, when passivity is maintained and the passivity regulator is inactive, the feedback force will track the slave force.

To have good responses using passivity regulation method, the master must have sufficient damping to dissipate the extra energy generated by the master due to discretization. Note that the damping is used to make the master passive, not the one-port network that includes the communication channel, controlled slave and the environment. The stabilization of the one-port network is guaranteed by the passivity regulator.

# CHAPTER 7 EXPERIMENTS

## 7.1 Experimental Setup

A test bed for the proposed approach has been set up. In the experimental setup, a Microsoft Sidewinder force feedback joystick is used as the master, and a PUMA 560 robot is used as the slave. The basic schematics is show in Figure .7.1
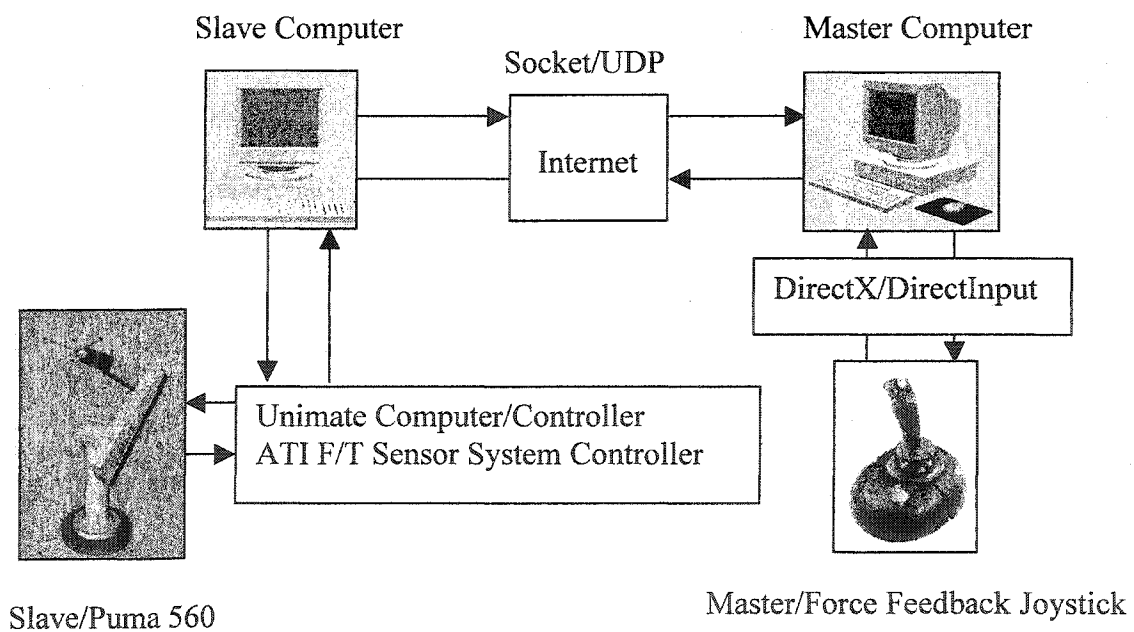


Figure 7.1  The schematics of experimental setup

The Puma 560 is a six degree-of-freedom robot, all six joints are rotational and actuated, while SideWinder force feedback joystick has three degrees of rotational freedom, but only two of them (right and left direction, back and forth direction) are actuated. In order to remotely control the PUMA using the force feedback joystick, controls have to be applied to "fix" the DOFs of the PUMA except 2 of them. These two degrees of freedom correspond to the two degrees of freedom on the joystick. During teleoperation, the back-and-forth motion on the joystick maps to the up-and-down motion on the PUMA, while left-and-right motion on the joystick corresponds to left-and-right motion on the PUMA. Although two degrees of freedom are matched between the joystick and the PUMA, only one degree of freedom is used to test the control scheme proposed in this work.

The PUMA 560 is equipped with a Trident robotics interface kit that allows control of the robot with a standard PC. To measure the force applied on the end effector by the environment, an Assurance Technologies six-axis force/torque transducer has been used. The force transducer is mounted between the end effector of the PUMA and the interface handle that touches the environment directly. This force transducer can measure forces up to 30 pounds and moments up to 100 inch pounds. In addition, it is configured with mechanical stop to prevent damage to the strain gauges in the transducer if forces or moments in excess of the rated limits are applied.

Both the PUMA and the joystick are connected to a PC respectively, and they can communicate with each other over the Internet. The network communication has been implemented using UDP type socket. In this setup, the joystick serves as the master, and sends out position information to the PUMA. The PUMA serves as the slave and is controlled to follow the motion of the joystick, and at the same time, sends the environmental

forces back to the joystick. Because of the kinematics and maximum force mismatch between the master and the slave, a proportion factor is used between them. In fact, the maximum load allowed on the force transducer is about 30 pounds, and the joystick is capable of much less than that. We use a conversion factor to match 100% measured load to 100% available joystick load.

The joystick is programmed using the DirectInput feature of Microsoft DirectX 8.1. The force is represented using a scale from 0 to 10000. In our program, we matched 10000 unit of force on the joystick to 28 pounds force sensed by the force transducer on the PUMA.

The PUMA is programmed to run at the frequency of 350 Hz, but the joystick only runs at the very low frequency of about 25 Hz.

In this research, the effective environmental stiffness felt at the PUMA 560 wrist was measured as *725.33N/m*. The corresponding rotational stiffness is *36.72Nm/rad*. The detail of the measurement method can be found in Appendix.

In order to protect the force transducer from physical damage during experiments. The environment is made up of plastic foam.

Since step input is a severe situation for a control system. In our experiments, we use a constant weight attached to the handle of the joystick through a pulley to provide a constant force. Although the dynamics of constant weight itself makes the force applied on the handle not always constant, this method is still challenging enough to test the control scheme.

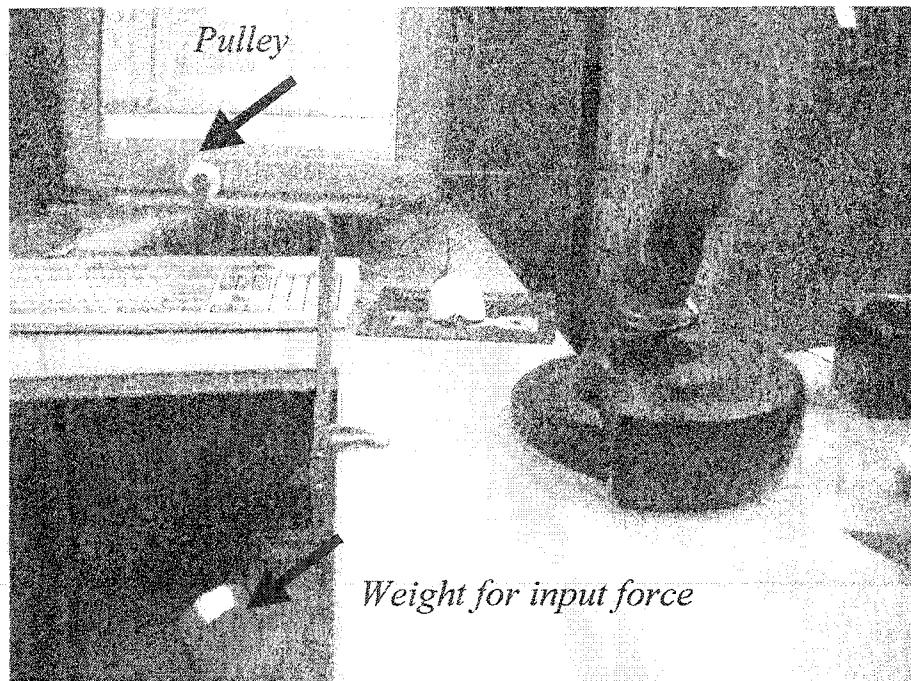The experimental setup is shown in Figure 7.2 to Figure 7.7.

Figure 7.2  A Microsoft Sidewinder force feedback joystick as master robot
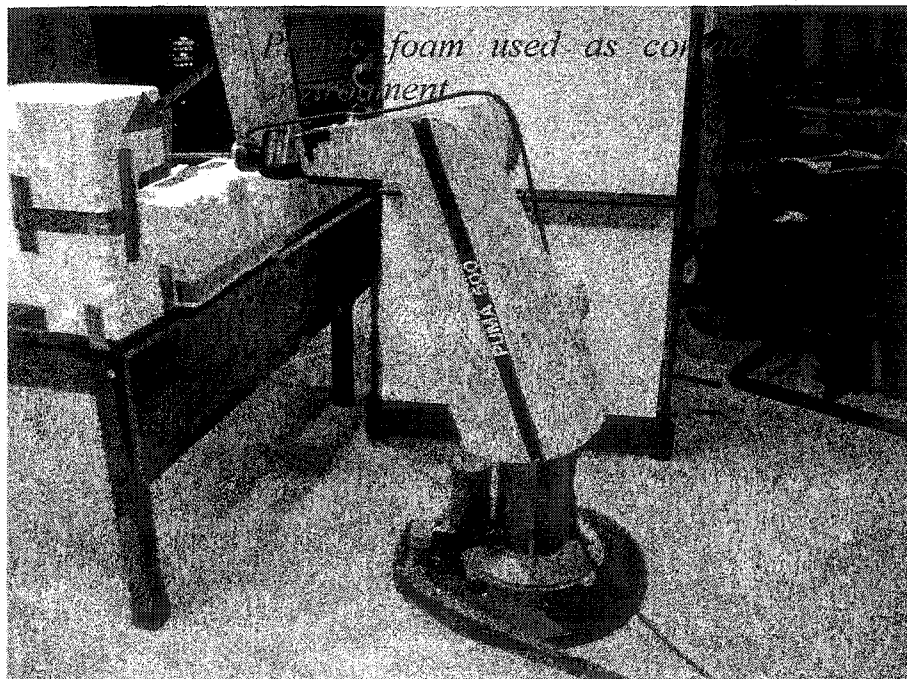


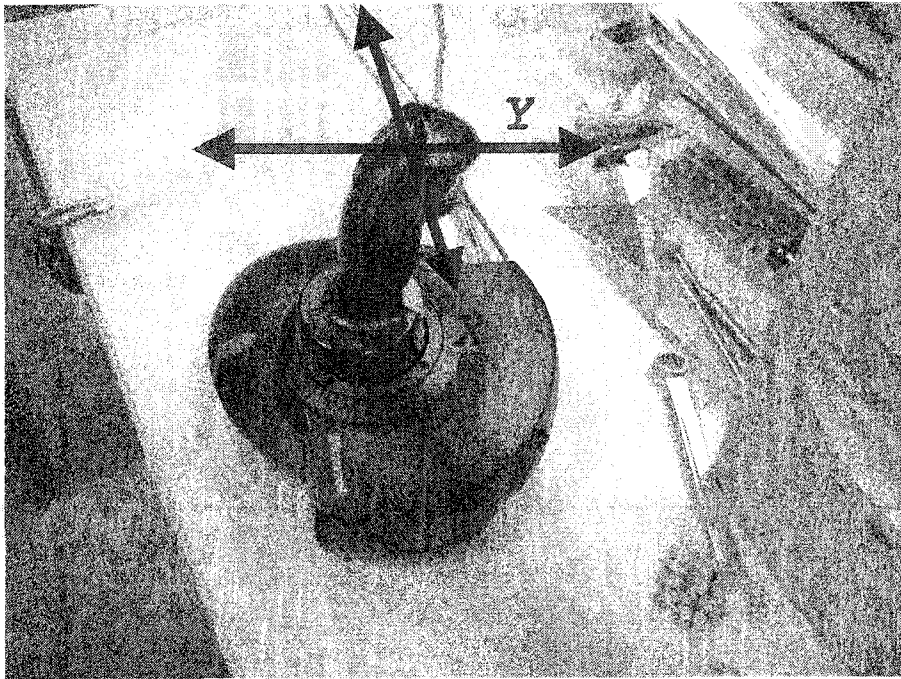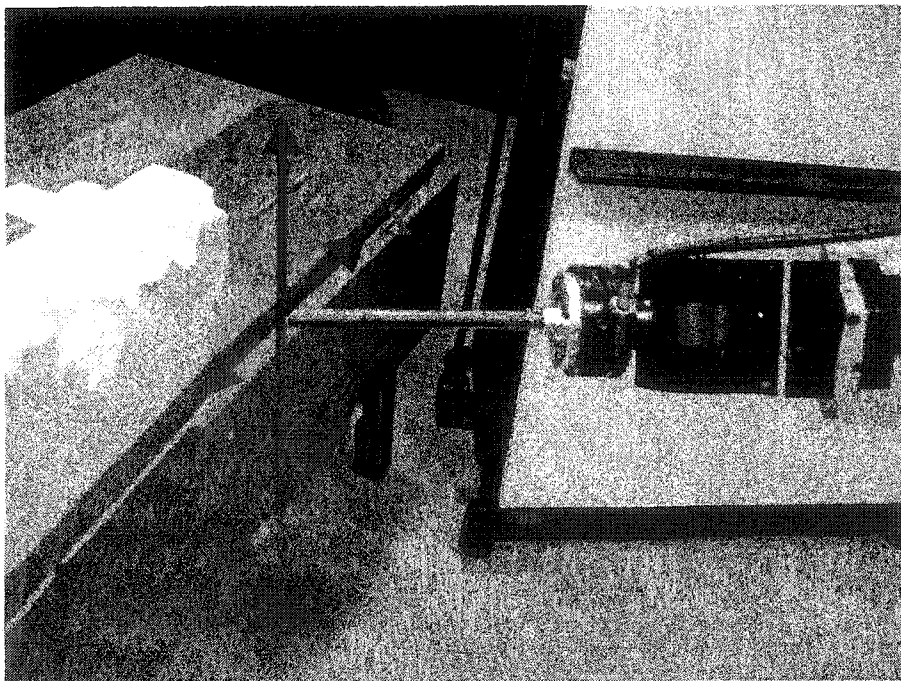Figure 7.3  A PUMA 560 as slave robot

Figure 7.4  Motion space of the master



Figure 7.5  Motion space of the slave

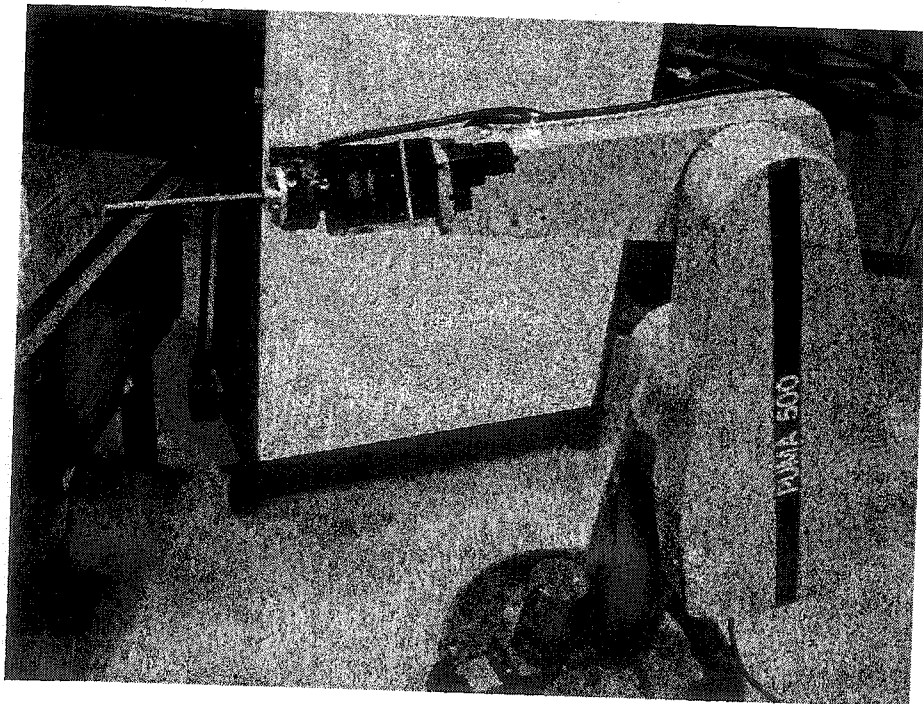Figure 7.6  The joystick is manipulated by an operator



Figure 7.7  Puma in action

## 7.2 Experimental Results

In the experiments, both the master and the slave are controlled by PCs. While those two computers do communicate with each other through the Internet using sockets and UDP protocol, they are in the same room. The delays caused by the Internet communication are less than 0.01 second and thus negligible. In order to investigate the effect of the time delays, we introduce an artificial delay between the two manipulators. During data transmissions, data packages are held for a pre-specified amount of time (forward time delay), after they are received by the slave computer from the master computer. Then these data packages are released and used as the desired position/velocity reference of the slave. At the same time, the force information acquired by the force/torque transducer is held for some other period of time (backward time delay, can be same with or different from the forward time delay) before being transmitted to the master computer through the Internet. The advantages of this method are, first, low cost and easier access to the data from both sides of the teleoperation system. Second, the control system can be programmed to test the system performance under different types of delays. The time delay from the master to the slave and that from the slave to the master can either be same or be different, and can be constants or variables, even random numbers.

Figures 7.8-10 show the system response with 0.2 second delay each direction. The figures show that the passivity regulator is activated for four short periods of time from 77.8 to 78.6 second. This means the passivity is lost and extra output energy needs to be dissipated for stable operations. It should be noted that extra damping has been used to improve the stability, since the passivity regulator just makes the one-port block loss-less.

Because the natural damping of the master manipulator (joystick) is minimal, the system response is highly oscillatory without extra artificial damping is being injected.

Figure 7.8 shows that the teleoperation system has a good position following performance, while it is easy to notice that there is a steady state error between the master and slave manipulator. This error is related to the position controller of slave. Better controller can be utilized to improve the system performance. It also shows that, there is some oscillation in master position response, which is because the passivity regulation lowered the feedback force at some moments, but the constant input force is still applied, and the changes of the force on the master results changes of the motion.
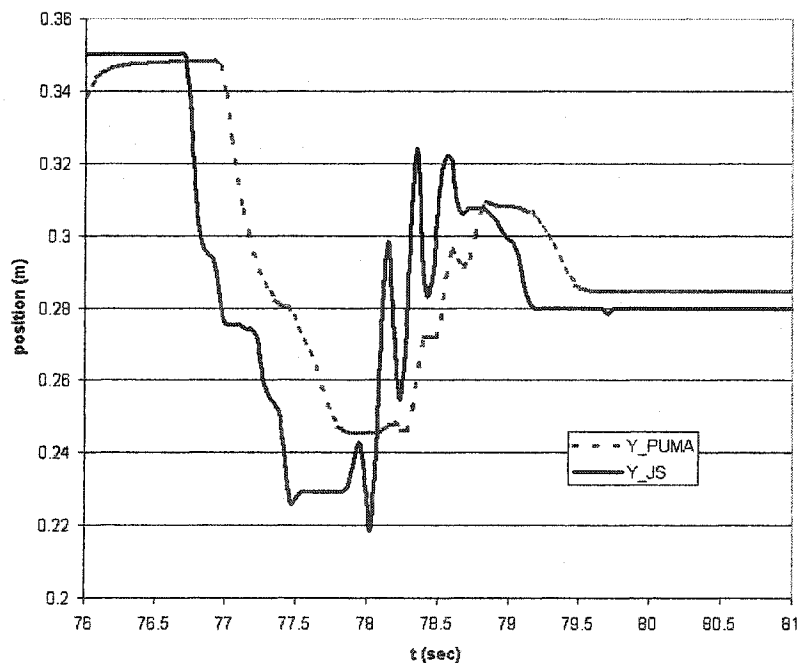


Figure 7.8 Master and slave position response

Also from Figure 7.8 to Figure 7.10, we can see the passivity regulator is triggered only when the master end-effector is bounced back after the contacts. This indicates that the one-port network has more energy to send back to the master than it has received. And the

position and force response converge to steady state after the first bounce. This is due to the

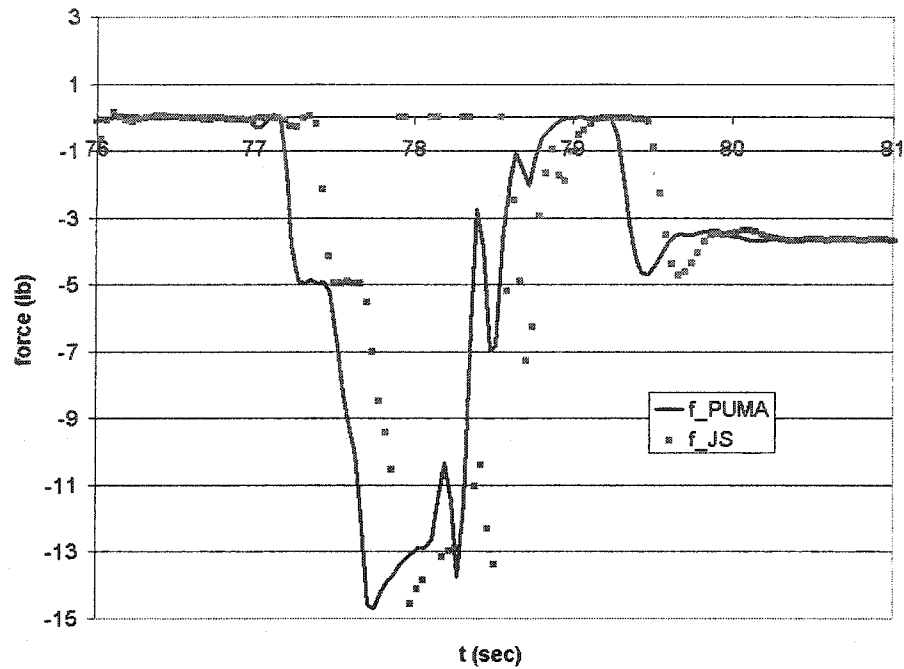joint efforts of the passivity regulator and the artificial damping.



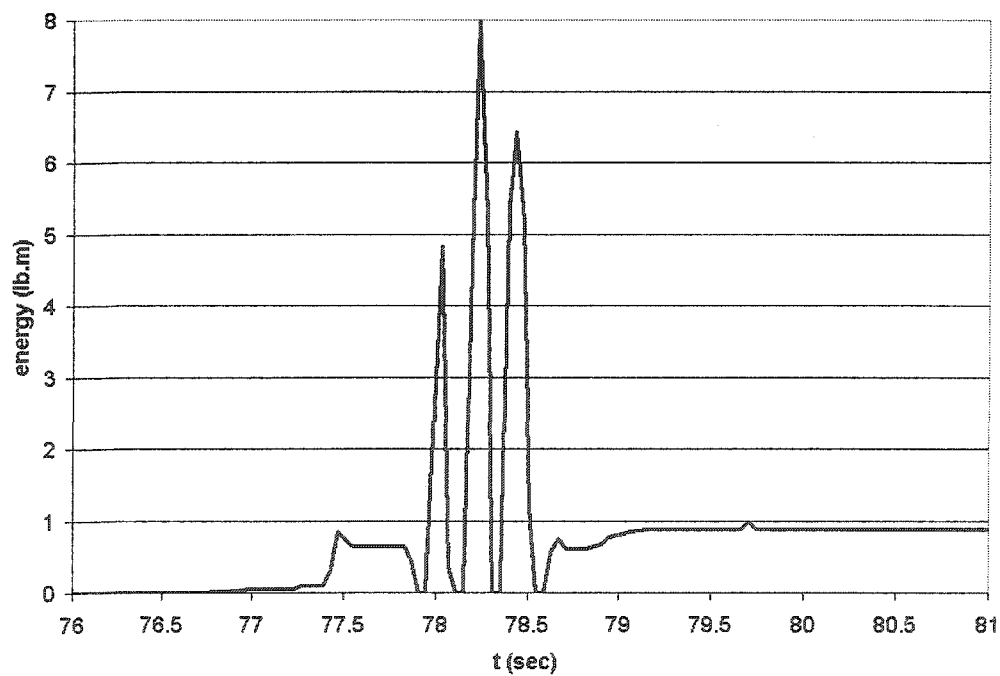Figure 7.9 Master and slave force response



Figure 7.10 Energy response

Under the same condition, Figure 7.11-13 show the results from another run of the experiment. Slightly different results are presented, but the same patterns can be seen.
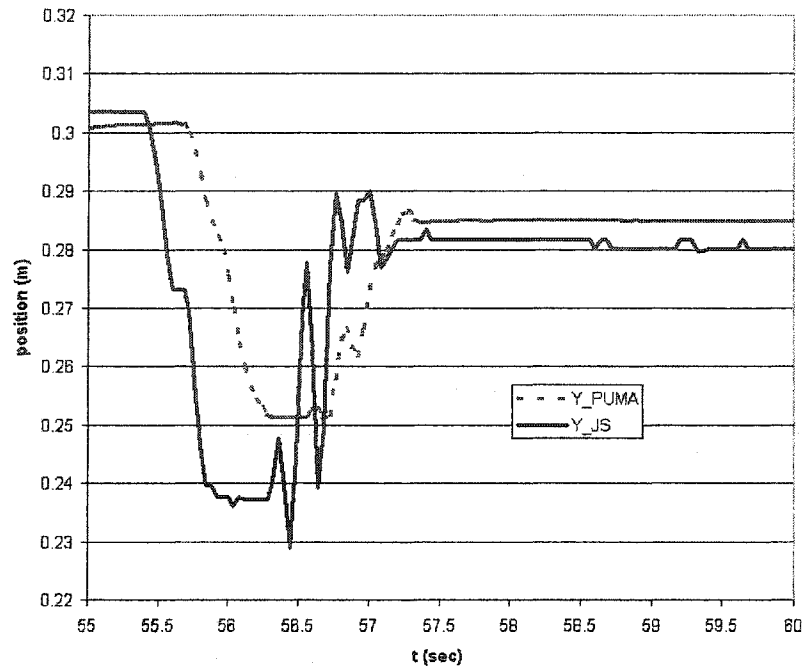


Figure 7.11  Master and slave position response (with 0.2 second delay)
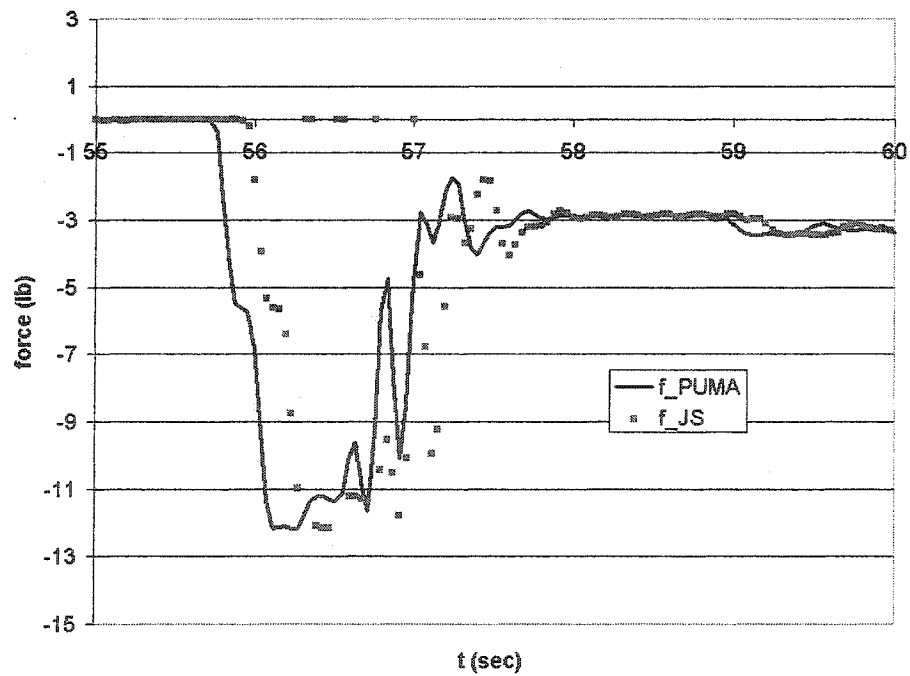


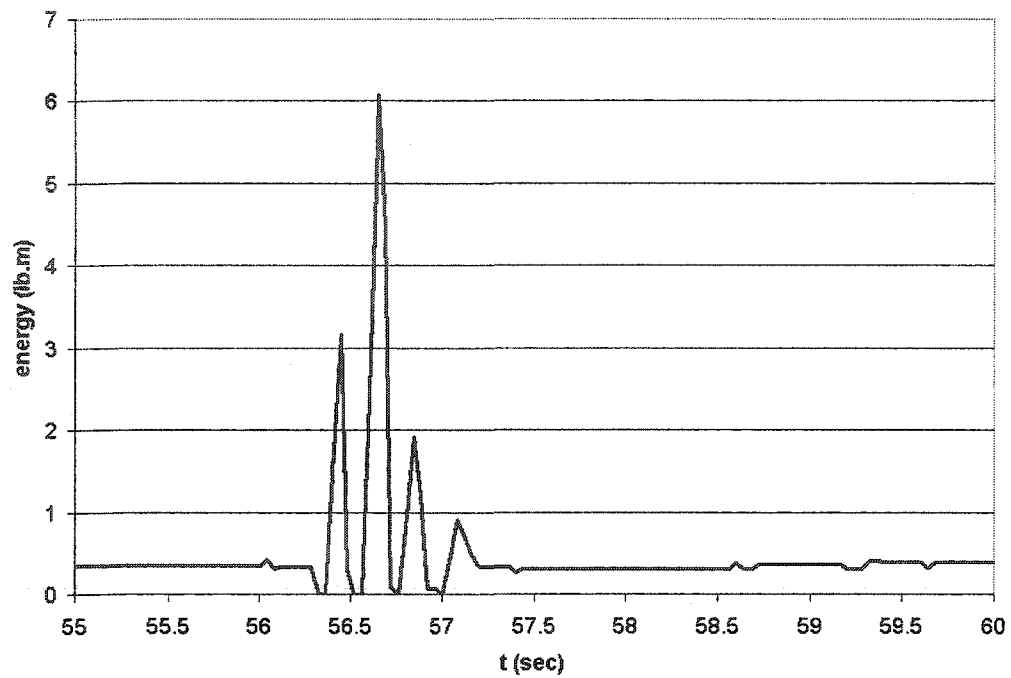Figure 7.12  Master and slave force response (with 0.2 second delay)

Figure 7.13  Energy response (with 0.2 second delay)

Figures 7.14-16 show the response of the system with forward time delay as 0.2 second and the backward delay as 0.3 second.
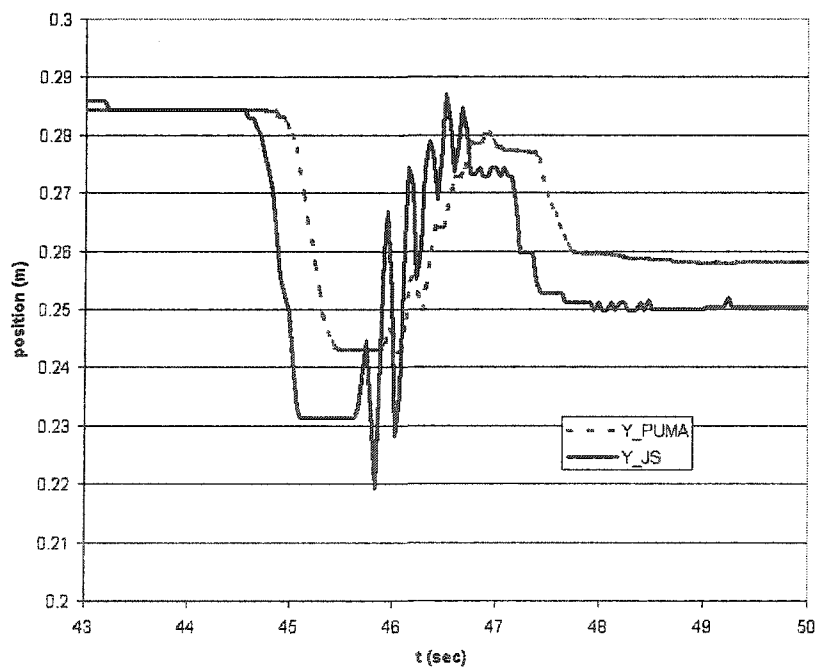


Figure 7.14  Master and slave position response

Figure 7.15 Master and slave force response
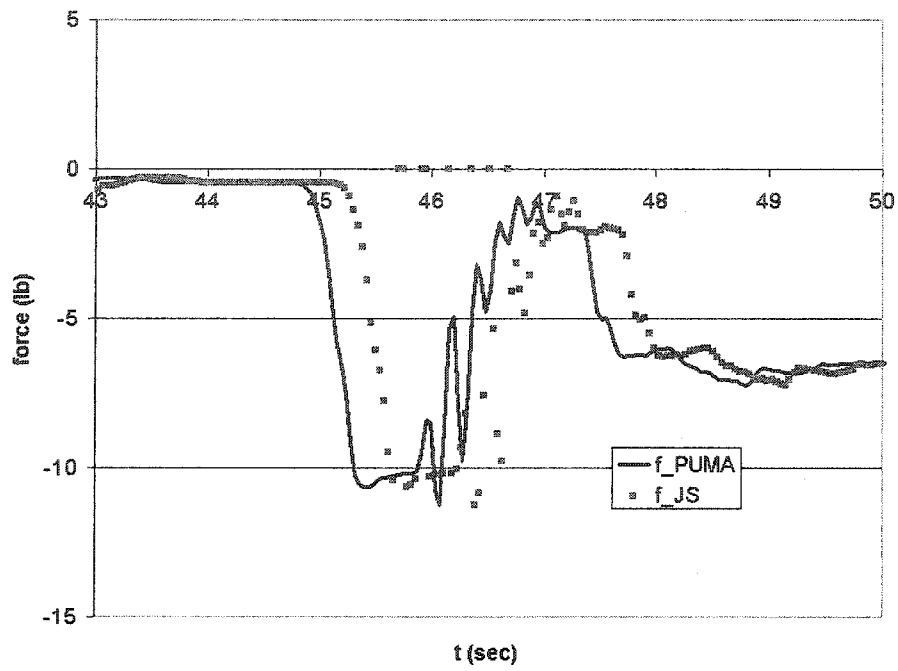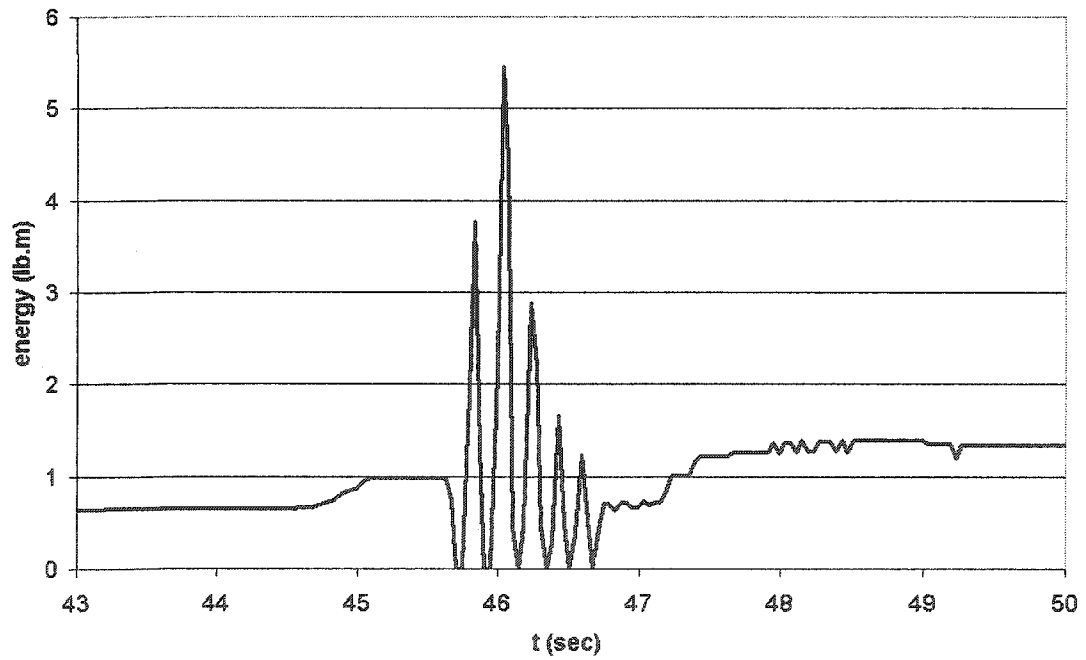


Figure 7.16 Energy response

82

As a comparison, system responses without passivity regulation are also tested. The results are given in Figure 7.17 and 7.18. The experimental results clearly show that the system without passivity regulation is unstable.
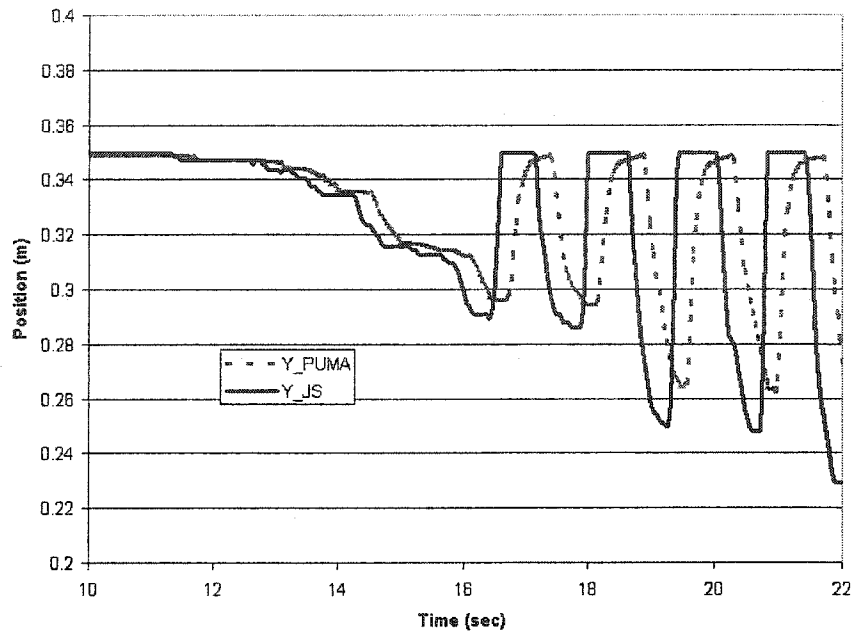


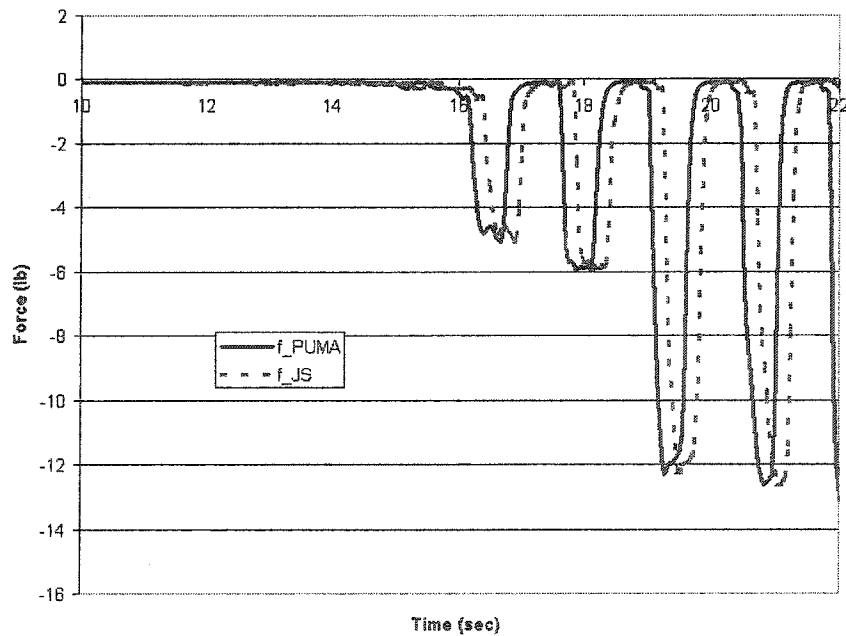Figure 7.17 Master and slave position response (no control)



Figure 7.18 Master and slave force response (no control)

Although a step force input to a teleoperation is a severe situation and it is very helpful to investigate system performance under step force input, most of the time, teleoperation systems are manipulated by human operators. Thus it is equally important to know how the system performs under the operation of human hands. Figure 7.19 to 7.21 show the position, force and energy response of the teleoperation system with hand input. In this experiment, the forward time delay is 0.3 second and backward time delay is 0.4 second. Figure 7.19-21 show better system performances than the cases in which constant forces are used. That is because the compliance of human hands helps to stabilize the system. When there are changes in the feedback forces, the hand force will change accordingly based on human instinct. This is different from the constant force input cases and thus decreases the oscillation in the system position and force responses.
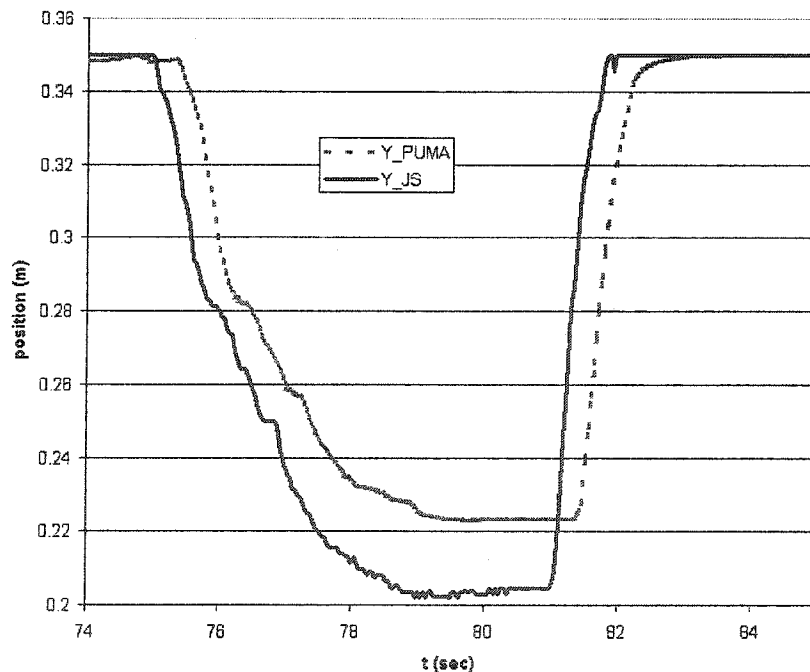


Figure 7.19 Master and slave position response (with hand input)
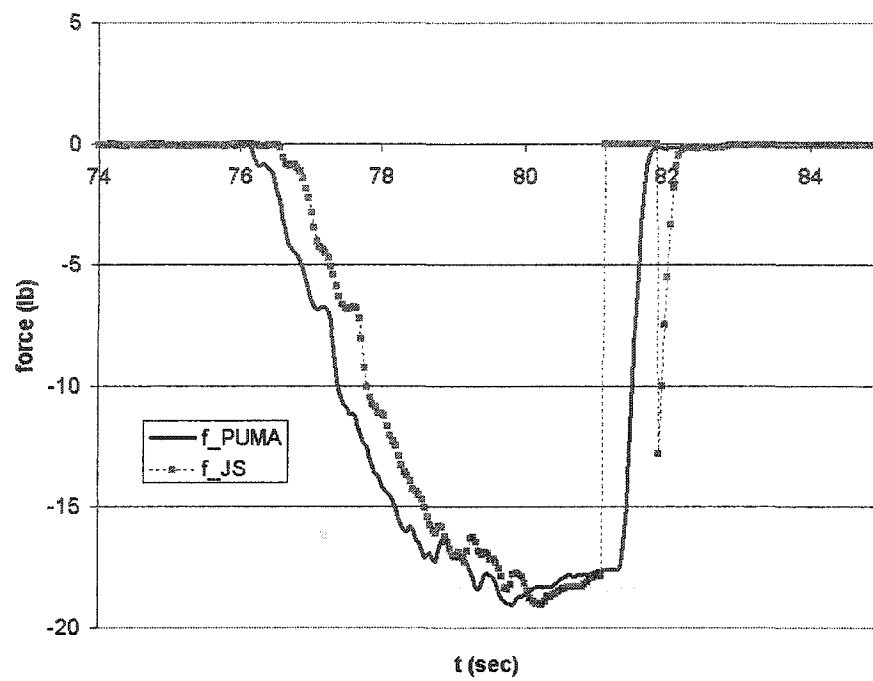
Figure 7.20  Master and slave force response (with hand input)
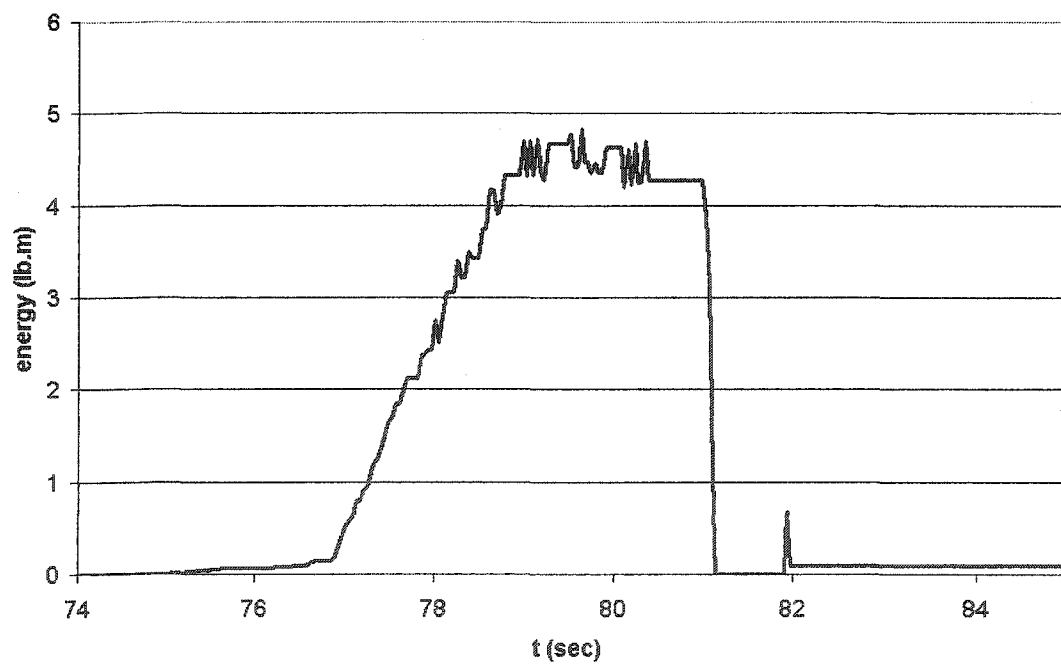


Figure 7.21  Energy response (with hand input)

Although a teleoperation system can be stabilized regardless of the time delays in the system, the system performance deteriorates with the increase of time delays. It is easy to understand that, because of the time delays, master manipulator can not sense the contact force at the same time as the slave can, master manipulator will have more overshoot when the delays increase as the slave is moving from free motion to a contact. An appealing remedy for this is add more damping. While it is true that more damping would slow down the master and decrease the overshoot, it would also make the master sluggish to move, and decrease the flexibility of the manipulations.

# CHAPTER 8 DISCUSSIONS AND CONCLUSIONS

The research in this project focused on the stabilization and control of teleoperation systems with time delays. The concept of passivity was used to design a control scheme to stabilize the teleoperation systems with minimal assumption. The validity of the method has been proved both analytically and experimentally. A teleoperation system has been set up at Iowa State University's Virtual Reality Application Center to test the approach.

In this work, a control scheme for teleoperation systems with time delay is proposed based on the concept of passivity. This control method requires neither the knowledge of the dynamic aspects of the manipulator system nor models of the environment, and it is applicable for any time delays. The model independence and time delay independence make the proposed control method well suitable for teleoperations in real world, including remote site explorations, tele-surgeries, space explorations and teleoperations through the Internet. The main contribution of this method is that it is less conservative than the traditional passivity based method. In our method, the passivity regulator only operates when the system loses passivity, while in a traditional passivity formulation, the controller works all the time during the operations that adversely affect the performance of the system. Our method can stabilize the system regardless of what have actually caused the instability.

Using the proposed control scheme, the part of the system composed of the communication channel, slave robot and the manipulated environment, is treated as a one-port network component. The energy flowing into the one-port network is monitored. When

the net inflow energy becomes negative, the passivity condition is violated, and the network starts to "generate" energy and thus causes system instability. To reinstate the passivity of the network, a passivity regulator is activated to regulate the feedback force to the master, and thus change the energy exchange between the master and the communication channel. The result is that the passivity of the system is maintained.

Because the use of this method requires only the information at the interface between the master robot and the communication channel, there is no need for detailed knowledge of the communications and slave sub-systems. The method can make the system passive, or, strictly speaking, lossless, regardless of whether the coordinating force or the true contact force is being fed back,. It can stabilize the system no matter what the cause of the instability might be, time delays or discretization of the physical plant. It has been shown that, using the contact force as feedback can significantly improve the free motion performance of the teleoperation systems. Using the passivity regulator prevents feedback of the contact force from destabilizing the system.

Besides the computer simulations, experiments have been performed to verify the proposed control scheme. A Microsoft Sidewinder force feedback Pro Joystick has been used as the master and a PUMA 560 robot has been used as the slave. The experimental results show that the proposed method can stabilize the teleoperation system with any time delays and with any working environments. Both simulations and experiments show satisfactory position and force following performance.

Since passivity regulation only guarantees the passivity of the one-port network, to have better performance, extra artificial damping has been injected to the master. This extra damping dissipates the possible excessive energy generated by the master due to

discretization. Passivity regulator dissipates the excessive energy generated by the communication channel, and possibly the slave and the environment. By combining the passivity regulator and the extra master damping. The teleoperation can be performed without instability concerns.

It should be noted that, although the method proposed in the dissertation can stabilize the system without excessive assumptions, it is not perfect. The activation of the passivity regulator generates some oscillations in system responses. Extra efforts are needed to smooth the responses.

# APPENDIX THE MEASUREMENT OF THE ENVIRONMENT STIFFNESS

To measure the environment stiffness, the teleoperation system was operated without a time delay. The master commanded the slave to push on the environment and the positions and the force measurements of the end effecter were recorded. Then the slope of the force position relation gave the stiffness information.
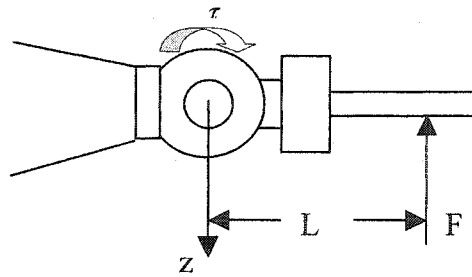


Figure 1 The end effecter of PUMA 560

Where we have the relation

$$\tau = FL \tag{1}$$

The rotation angle of the wrist joint can be calculated using

$$\theta = \frac{dz}{L} \tag{2}$$

where *dz* is the displacement of the wrist joint.

When the information of the position and the torque at the wrist joint is acquired, the stiffness felt by the joint can be computed as

$$K_J = \frac{d\tau}{d\theta} = \frac{dF}{dz} L^2 \qquad (3)$$

In our experiments, the plastic foam was used as environment. The sample measurement result is shown in the figure below

**Fz-Z**
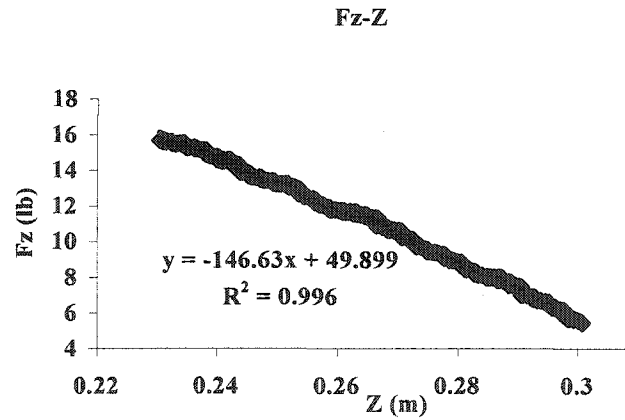


Figure 2 The relation of the wrist position and the joint force

In the experiments, L, the distance between the wrist joint and the point on which the environmental forces were applied is 0.225 meter. From equation (3), for the result shown in Figure 2, the environment stiffness is

$$K_J = \frac{d\tau}{d\theta} = \frac{dF}{dz} L^2$$

$$= 146.63 lb / m * 4.448 N / lb * 0.225^2 m^2$$

$$= 33.02 N.m / rad$$



Figure 3 The measured stiffness at the wrist

From the experimental results, the environment stiffness felt at the wrist joint can be found by averaging the results

$$K_{Jave} = 36.72 \, Nm / rad$$

The linear stiffness felt at the wrist is then

$$K = \frac{K_{Jave}}{L^2} = \frac{36.72 \, Nm / rad}{0.225^2 \, m^2} = 725.33 N / m$$

# BIBLIOGRAPHY

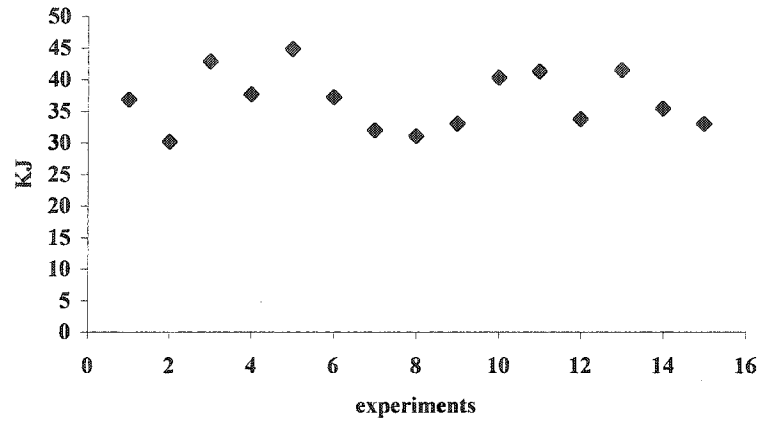[1]     T. B. Sheridan, "Telerobotics," *Automatica*, vol. 25, pp. 487-507, 1989.

[2]     R. Goertz and R. Thompson, "Electronically controlled manipulator," *Nucleonics*, 1954.

[3]     A. Malinowski and B. Wilamowski, "Controlling robots via Internet," presented at 1st International Conference on Information Technology in Mechatronics, Istanbul, Turkey, 2001.

[4]     W. R. Ferrel, "Remote manipulation with transmission delay," *IEEE Transactions on Human Factors in Electronics*, pp. 24-32, 1965.

[5]     W. R. Ferrel and T. B. Sheridan, "Supervisory control of remote manipulator," *IEEE Spectrum*, vol. 4, pp. 81-88, 1967.

[6]     M. A. Sitti, B.; Shintani, H.; Hashimoto, H., "Development of a scaled teleoperation system for nano scale interaction and manipulation," presented at IEEE International Conference on Robotics and Automation, Seoul, Korea, 2001.

[7]     K. Takeo and K. Kosuge, "Implementation of the micro-macro teleoperation system without using slave-side force sensors," presented at IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, 1997.

[8]     T. Fong, C. Thorpe, and C. Baur, "Advanced interfaces for vehicle teleoperation: collaborative control, sensor fusion displays, and remote driving tools," *Autonomous Robots*, vol. 11, pp. 77-85, 2001.

[9]     T. Fong, C. Thorpe, and C. Baur, "Multi-robot remote driving with collaborative control," *IEEE Transactions on Industrial Electronics*, vol. 50, pp. 699-704, 2003.

[10]    B. Hannaford and R. J. Anderson, "Experimental and simulation studies of hard contact in force reflecting teleoperation," presented at IEEE Conference on Robotics and Automation, Philadelphia, PA, 1988.

[11]    Y. Yokokohji and T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling - formulation and experiment," *IEEE Transactions on Robotics and Automation*, vol. 10, pp. 605-619, 1994.

[12]    S. E. Salcudean, M. Zhu, W.-H. Zhu, and K. Hashtrudi-Zaad, "Transparent bilaterial teleoperation under position and rate control," *International Journal of Robotics Research*, vol. 19, pp. 1185-1202, 2000.

[13]    D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Transactions on Robotics and Automation*, vol. 9, pp. 624-637, 1993.

[14]    N. Xi and T. J. Tarn, "Action synchronization and control of internet based teleorobotic systems," presented at IEEE International Conference on Robotics and Automation, Detroit, Michigan, 1999.

[15]    R. Oboe and P. Fiorini, "Issues on internet-based teleoperation," presented at the Fifth IFAC Symposium on Robot Control, Nantes, France, 1997.

[16]    J. C. Bolot, A. U. Shankar, and B. D. Plateau, "Performance analysis of transport protocols over congestive networks," *Journal on performance evaluation*, vol. 11, pp. 45, 1990.

[17]    R. J. Anderson and M. W. Spong, "Hybrid impedance control of robotic manipulators," *IEEE Journal of Robotics and Automation*, vol. 4, pp. 549-556, 1988.

[18] R. J. Anderson and M. W. Spong, "Network representation for robots," in *Recent Advances in Control of Nonlinear and Distributed Parameter Systems, Robust Control and Aerospace Control Applications,Nov 27-Dec 2 1988*, vol. 10, *American Society of Mechanical Engineers, Dynamic Systems and Control Division (Publication) DSC*. Chicago,IL,USA: Publ by American Soc of Mechanical Engineers (ASME),New York,NY,USA, 1988, pp. 71-78.

[19] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Transactions on Automatic Control*, vol. 34, pp. 494-501, 1989.

[20] R. J. Anderson and M. W. Spong, "Asymptotic stability for force reflecting teleoperators with time delay," presented at IEEE International Conference on Robotics and Automation, Scottsdale, AZ, USA, 1989.

[21] R. J. Anderson and M. W. Spong, "Asymptotic stability for force reflecting teleoperators with time delay," *International Journal of Robotics Research*, vol. 11, pp. 135-149, 1992.

[22] R. J. Anderson and B. Davies, "Using virtual objects to aid underground storage tank teleoperation," presented at IEEE International Conference on Robotics and Automation, 1994.

[23] R. J. Anderson, "Autonomous, teleoperated, and shared control of robot systems," presented at IEEE International Conference on Robotics and Automation, 1996.

[24] G. Niemeyer and J.-J. E. Slotine, "Transient shaping in force-reflecting teleoperation," presented at International Conference on Advanced Robotics, 1991.

[25] G. Niemeyer and J.-J. E. Slotine, "Stable Adaptive Teleoperation," *IEEE Journal of Oceanic Engineering*, vol. 16, pp. 152-162, 1991.

[26]    G. Niemeyer and J.-J. E. Slotine, "Using wave variables for system analysis and robot control," presented at IEEE International Conference on Robotics and Automation, 1997.

[27]    G. Niemeyer and J.-J. E. Slotine, "Designing force reflecting teleoperators with large time delays to appear as virtual tools," presented at IEEE International Conference on Robotics and Automation, 1997.

[28]    G. Niemeyer and J.-J. E. Slotine, "Towards force-reflecting teleoperation over the Internet," presented at IEEE International Conference on Robotics and Automation, 1998.

[29]    G. M. H. Leung, B. A. Francis, and J. Apkarian, "Bilaterial Control for teleoperators with Time Delay via mu_Synthesis," *IEEE Transactions on Robotics and Automation*, vol. 11, pp. 105-116, 1995.

[30]    S. Munir and W. J. Book, "Internet-based teleoperation using wave variable with prediction," *IEEE/ASME Transactions on Mechatronics*, vol. 7, pp. 124-133, 2002.

[31]    K. Kosuge, H. Murayama, and K. Takeo, "Bilateral feedback control of telemanipulators via computer network," presented at IEEE/RSJ International Conference on Intelligent Robots and System (IROS'96), 1996.

[32]    Y. Yokokohji, T. Imaida, and T. Yoshikawa, "Bilateral teleoperation under time-varying communication delay," presented at 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'99), Kyongju, South Korea, 1999.

[33]    Y. Yokokohji, T. Imaida, and T. Yoshikawa, "Bilateral control with energy balance monitoring under time-varying communication delay," presented at IEEE

International Conference on Robotics and Automation, San Francisco, CA, USA, 2000.

[34] K. J. Brady and T.-J. Tarn, "Internet-based teleoperation," presented at IEEE International Conference on Robotics and Automation, Seoul, Korea, 2001.

[35] N. Xi, T. J. Tarn, and A. K. Bejczy, "Intelligent planning and control for multirobot coordination: an event based approach," *IEEE Transactions on Robotics and Automation*, vol. 12, 1996.

[36] I. Elhajj, N. Xi, and Y. H. Liu, "Real-time control of internet based teleoperation with force reflection," presented at IEEE International Conference on Robotics & Automation, San Francisco, CA, 2000.

[37] I. Elhajj, J. Tan, N. Xi, W. K. Fung, Y. H. Liu, T. Kaga, Y. Hasegawa, and T. Fukuda, "Multi-site internet-based coorperative control of robotic operation," presented at IEEE/RSJ International Coference on Intelligent Robots and Systems, Takamatsu, 2000.

[38] I. Elhajj, N. Xi, W. K. Fung, Y. H. Liu, Y. Hasegawa, and T. Fukuda, "Multi-site real-time tele-cooperation via the Internet," *Advanced Robotics*, vol. 17, pp. 235-251, 2003.

[39] R. Oboe, "Web-interfaced, force-reflecting teleoperation systems," *IEEE Transactions on Industrial Electronics*, vol. 48, pp. 1257-1265, 2001.

[40] K. Hashtrudi-Zaad and S. E. Salcudean, "Transparency in time-delayed systems and effect of local force feedback for transparent teleoperation," *IEEE Transactions on Robotics and Automation*, vol. 18, pp. 108-114, 2002.

[41]  M. C. Cavusoglu, A. Sherman, and F. Tendick, "Design of bilateral teleoperation controllers for haptic exploration and teleoperation of soft environments," *IEEE Transactions on Robotics and Automation*, vol. 18, pp. 641-647, 2002.

[42]  B. Hannaford and J.-H. Ryu, "Time-domain passivity control of haptic interfaces," *IEEE Transactions on Robotics and Automation*, vol. 18, pp. 1-10, 2002.

[43]  J.-H. Ryu, D.-S. Kwon, and B. Hannaford, "Stable teleoperation with time domain passivity control," presented at 2002 IEEE International Conference on Robotics and Automation, Washington, DC, 2002.

[44]  J.-H. Ryu, D.-S. Kwon, and B. Hannaford, "Stable teleoperation with time-domain passivity control," *IEEE Transactions on Robotics and Automation*, vol. 20, pp. 365-373, 2004.

[45]  T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, Massachussette: MIT Press, 1992.

[46]  J. Fiala and R. Lumia, "The effect of time delay and discrete control on the contact stability of simple position controllers," *IEEE Transactions on Automatic Control*, vol. 39, pp. 870-873, 1994.

[47]  J. E. Colgate, "The control of dynamically interacting systems," MIT, 1988.

[48]  E. Colgate and N. Hogan, "An analysis of contact instability in terms of passive physical equivalents," presented at IEEE International Conference on Robotics and Automation, Scottsdale, AZ, 1989.

[49]  J.-J. E. Slotine and W. Li, *Applied Nonlinear Control*: Prentice Hall, 1991.

[50]  B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE Transactions on Robotics and Automation*, vol. 5, pp. 426-434, 1989.

[51]    D. E. Comer and R. E. Droms, *Computer Networks and Internets, with Internet Applications*, 3 ed: Prentice Hall, 2001.

[52]    D. E. Comer, *Interconnecting with TCP/IP*: Prentice Hall, 1991.

[53]    G. M. H. Leung and B. A. Francis, "Bilateral control of teleoperators with time delay through a digital communication channel," presented at Thirtieth Ann. Allerton Conf. Commun., Contr., 1992.