

Bilateral Control of Base-Excited Hydraulic Manipulators Operating under a Delayed and Lossy Network

by

Yaser Maddahi

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfillment of the requirements of the degree of

Doctor of Philosophy

Department of Mechanical and Manufacturing Engineering
The University of Manitoba
Winnipeg, Manitoba, Canada

Copyright © 2013 by Yaser Maddahi

ABSTRACT

Teleoperation of hydraulic manipulators is of potential when the presence of the operator, in a remote location, is inconvenient or dangerous. Augmenting such teleoperated systems using haptic sensation will further enhance performance, safety, and convenience. The advantage of using haptic force becomes more evident when it is employed to compensate for undesirable phenomena such as existence of a delayed and lossy communication channel or excitation of the manipulator base. The focus of this thesis is on haptic-enabled control of base-excited hydraulic manipulators that are controlled through a wireless communication channel. The targeted application is live transmission line maintenance.

Both unilateral and bilateral controls of teleoperated hydraulic manipulators are studied. On the unilateral front, position error is shown to be an important issue, especially when the position accuracy of the slave manipulator is violated due to fast motion of the operator's hand at the master site, lack of responsiveness in actuation system, or poor quality of communication channel. With respect to bilateral control, three main challenges are identified, and solutions to these challenges are investigated: (i) accurate control of the slave manipulator when the communication channel is delayed and/or lossy, (ii) control of the teleoperated system when the slave manipulator is mounted atop a moving platform, and (iii) transparent force feedback to improve the position tracking of the system.

First, effects of network quality and slave manipulator base excitation are examined on performance of the teleoperated system. The position error between the haptic device implement and the hydraulic manipulator end-effector is shown to increase when the

network is delayed and lossy. Next, excitation of the slave manipulator base deviates the end-effector from its reference trajectory, and the position error therefore becomes larger. To alleviate the position inaccuracy, a position referenced force feedback scheme is proposed. The scheme makes the input dynamics a better match with the slave dynamics. Combined with the virtual fixture force, the virtual fixture is shown to aid the operator in following a predefined virtual fixture trajectory. Due to complexity of dynamics, performance evaluations are mostly conducted using experimental validations on actual system in a laboratory setting.

MATLAB is copyright The Math Works, Inc. 1994-2013

SIMULINK is copyright The Math Works, Inc. 1994-2013

RStudio is a trademark of RStudio, Inc. 2013

ACKNOWLEDGMENT

My first acknowledge needs to go to my advisor, Dr. Nariman Sepehri, whose guidance, support, and encouragement have always been invaluable. Working in his research group has been a joy and privilege. Thanks to Dr. Subramaniam Balakrishnan, Dr. Ekram Hossain, and Dr. Wai-keung Fung for serving on my advisory committee. Special thanks to Dr. Reza Fotouhi from the University of Saskatchewan for serving on my PhD examining committee.

Thanks to Mr. Ehsan Jalayeri, Dr. Kourosh Zareinia and Mr. Ramhuzaini A. Rahman for help with the experimental test rigs. They have also been a valuable sounding board for numerous ideas. In producing the results shown in Chapter 4, Mr. Stephen Liao contributed in helping to set up the wireless emulation environment. Help from Mr. Vikram Banthia in programming the motion base to emulate the base movement is greatly appreciated.

Thanks to NSERC, Manitoba Hydro, MITACS, and the University of Manitoba for providing financial support for this work. A thanks is due to technical advice given by Mr. Tim Olson from Manitoba Hydro. I would also like to acknowledge comments and suggestions from anonymous reviewers who have critiqued some of the work presented as articles in journals and conferences.

Special thanks are also due to my wife, Maryam, for encouragement and for supplying incentive to finish. Special thanks to my parents and brothers who encouraged me to develop my strengths, and work hard on my weaknesses.

Thanks to all of my peers in the “Fluid Power and Telerobotics Research Laboratory” at the University of Manitoba. It has been a pleasure working with all of them. Lastly, I

would like to thank all of the friends during my years at the University of Manitoba who supplied the ridiculous moments to compliment my otherwise sublime life as a graduate student.

TABLE OF CONTENT

CHAPTER 1	1
1 INTRODUCTION	1
1.1. Statement of the Problem	1
1.2. Objectives of the Research	3
1.3. Scope of the Research	4
1.4. Thesis Outline	7
CHAPTER 2	9
2. RELEVANT BACKGROUND	9
2.1. Application Area of Interest	9
2.2. Review of Teleoperated Systems	14
2.3. Haptic-Enabled Teleoperation: Concept	15
2.3.1. Definition	15
2.3.2. Master position referenced force	17
2.3.3. Slave position referenced force	18
2.3.4. Impedance vs. admittance	19
2.4. Network Quality in Teleoperation	21
2.5. Teleoperation of Mobile Manipulators	24
CHAPTER 3	26
3. EXPERIMENTAL TEST RIGS AND MODELING	26
3.1. General Description of the System	26
3.2. Description of the Sub-Systems	27
3.2.1. Slave hydraulic actuator	27
3.2.2. Slave hydraulic manipulator	32
3.3. Hand-Controllers	40
3.4. Network Emulators	43
3.4.1. General architecture	43
3.4.2. Wide Area Network emulator (WANem)	44
3.4.3. Network simulator version 2 (NS2)	45
3.5. Summary	47

CHAPTER 4	48
4. WIRELESS CONTROL OF HYDRAULIC ACTUATORS	48
4.1. Introduction.....	48
4.2. Performance Evaluation under Dedicated Channels.....	49
4.2.1. Test procedure.....	49
4.2.2. Control schemes.....	51
4.2.3. Experimental results using simulation of hydraulic actuator.....	54
4.2.3.1 Position tracking	54
4.2.3.2 Force tracking	59
4.2.3.3 Discussions	62
4.2.3.4 Perceived stiffness	65
4.3. Performance Evaluations under Wireless Channels	67
4.3.1. Implementation of wireless channel	67
4.3.2. Establishing maximum allowable delay and packet loss.....	70
4.3.3. Constructing performance charts	76
4.3.4. Further experimental validations	80
4.4. Summary.....	85
CHAPTER 5	88
5. UNILATERAL AND BILATERAL CONTROLS FOR HYDRAULIC MANIPULATORS.....	88
5.1. Introduction.....	88
5.2. Master Position Referenced (Virtual Fixture) Scheme: Unilateral Control.....	89
5.2.1. Coordinate mapping.....	89
5.2.2. Implementation and results.....	95
5.3. Slave Position Referenced (Force Augmentation) Scheme: Bilateral Control	103
5.4. Augmented Virtual Fixture Scheme: Bilateral Control	107
5.5. Experimental Results	108
5.6. Summary	114
CHAPTER 6	116
6. POSITION REFERENCED FORCE AUGMENTATION APPLIED TO DELAYED TELEMNIPULATORS	116
6.1. Introduction.....	116

6.2. Description of the Scheme	117
6.3. Test Procedure	117
6.4. Results	119
6.4.1. Experiments using dedicated channel	119
6.4.2. Experiments using wireless channel	122
6.5. Summary	127
CHAPTER 7	129
7. WIRELESS CONTROL OF BASE-EXCITED TELEMANIPULATORS	129
7.1. Introduction	129
7.2. Design of Experiments	130
7.2.1. Network setup	130
7.2.2. Base motion	131
7.2.3. Control scheme	133
7.3. Test Procedure	133
7.4. Results	135
7.5. Summary	140
CHAPTER 8	141
8. CONCLUSIONS	141
8.1. Contributions of this Thesis	141
8.2. Future Work	142
Appendix - Questionnaire	144
References	145

TABLE OF FIGURES

Figure 2.1 Conducting live-line maintenance near energized lines.	10
Figure 2.2 Typical maintenance tasks: (a) Task A: pulling out a cotter pin; (b) Task B: loosening or tightening a nut; (c) Task C: connecting or disconnecting a ball and socket joint; (d) Task D: inserting a cotter pin; (e) Task E: twisting a tie wire around cable.	11
Figure 2.3 Concept developed to perform live-line maintenance near energized lines. A lineman uses a hand-controller to control manipulator at a distance.	13
Figure 2.4 Elements of a teleoperated system. Dashed arrows indicate the direction of information flow.	15
Figure 2.5 (a) Unilateral and (b) bilateral teleoperated systems.	15
Figure 2.6 Sign convention in admittance-type and impedance-type teleoperated systems.	20
Figure 2.7 Virtual spring pulls operator's hand toward desired trajectory. End-effector position can be on-track ($F = 0$) or off-track ($F \neq 0$).	21
Figure 2.8 Network communication setup between master and slave sites.	22
Figure 3.1 General architecture of teleoperated test rig. Dashed lines indicate UDP connection.	27
Figure 3.2 Teleoperated hydraulic actuator setup.	28
Figure 3.3 Schematics of hydraulic actuator interacting with a stiffness dominant environment.	28
Figure 3.4 Teleoperated hydraulic manipulator setup.	33
Figure 3.5 Coordinate frames of slave hydraulic manipulator.	35
Figure 3.6 Coordinate systems of Stewart platform.	38
Figure 3.7 Schematic of a manipulator link driven by a single-rod hydraulic actuator.	40
Figure 3.8 Coordinate frames of conventional seven-function joystick.	41
Figure 3.9 Coordinate frames of PHANToM Desktop/Omni haptic device.	42
Figure 3.10 Network communication setup.	43
Figure 3.11 WANem architecture.	44
Figure 3.12 Protocol stack of NS2 in emulation mode. Shaded boxes indicate components that are part of NS2. Solid and dashed lines indicate physical and logical connections, respectively.	47
Figure 4.1 Typical trajectory for haptic device showing master displacement, x_m	50
Figure 4.2 Displacements, x_m and x_s ; solid line: haptic device (master); dashed line: hydraulic actuator (slave). Responses are shown for TD=100 ms and PL=75% (UD30), for TD=100 ms and PL=0% (UD00), and for TD=1000 ms and PL=0% (UD02).	56

Figure 4.3 Displacement errors when PL=0%. Dotted line: TD=100 ms (UD00); solid line: TD=500 ms (UD01); dashed line: TD=1000 ms (UD02).....	58
Figure 4.4 Effect of time delay on RMS value of position errors (number of runs=48)..	59
Figure 4.5 Forces produced by haptic device (solid line), and generated by the hydraulic actuator (dashed line), for all scenarios defined in Table 4.1.	60
Figure 4.6 Effect of time delay on force tracking error for PL=0%, 25%, 50% and 75%.	61
Figure 4.7 Control signals: TD=100 ms and PL=75% (UD30), TD=100 ms and PL=0% (UD00), and TD=1000 ms and PL=0% (UD02).....	63
Figure 4.8 Effect of time delay on stiffness perceived by operator for PL=0%, TD=1000 ms (solid line) and PL=0%, TD=100 ms (dashed line). Arrows indicate actual stiffness of spring.....	65
Figure 4.9 Effect of packet loss on stiffness perceived by operator for PL=50%, TD=100 ms (solid line) and PL=25%, TD=100 ms (dashed line). Arrows indicate actual stiffness of spring.	66
Figure 4.10 Probability of dropping a packet when $\sigma=4$ and $n=2.7$	70
Figure 4.11 Typical trajectory of hydraulic actuator coordinated by haptic device.	72
Figure 4.12 Network characteristics (single-way delay and packet loss) used to find the maximum allowable delay and packet loss.....	73
Figure 4.13 Experimental results pertaining first network scenario using PHANToM device, NS2 simulator and simulation of hydraulic actuator; (a) displacements at master and slave sites; (b) forces produced by haptic device.....	75
Figure 4.14 Experimental results pertaining second network scenario using PHANToM device, NS2 simulator and simulation of hydraulic actuator; (a) displacements at master and slave sites, (b) forces produced by haptic device.....	75
Figure 4.15 (a) Experimental field test setup; (b) master site: operator, haptic device, master PC, and wireless router; (c) slave PC.....	76
Figure 4.16 Performance chart of the guideline designed to select network parameters for hydraulic actuator.....	79
Figure 4.17 Variations of time delay over a 5-second period for scenarios defined in Table 4.4.	81
Figure 4.18 Variations of packet loss over a 5-second period for scenarios defined in Table 4.4.	81
Figure 4.19 Position tracking of hydraulic actuator end-effector (dashed line), and haptic device implement (solid line) for scenarios S01 to S12.	83
Figure 4.20 Forces produced by haptic device (dashed line), and generated by hydraulic actuator (solid line), for scenarios S01 to S12.	83
Figure 4.21 Position of hydraulic actuator end-effector (dashed line), and haptic device implement (solid line) under scenarios defined within acceptable and marginal regions.	84

Figure 4.22 Force produced by haptic device (dashed line), and generated by the hydraulic actuator (solid line), for scenarios defined within acceptable and marginal regions.....	84
Figure 5.1 Block diagram of teleoperated hydraulic manipulator using JM mode. Joint angular displacements of joystick are the desired angular displacements of manipulator joints.....	91
Figure 5.2 Block diagram of teleoperated control system in EM mode.	91
Figure 5.3 (a) Virtual spring pulls operator's hand toward desired trajectory; (b) desired and actual positions of haptic implement.....	92
Figure 5.4. Block diagram of hydraulic telemanipulator using VF scheme..	94
Figure 5.5 Typical test trajectories of hydraulic manipulator end-effector under JM, EM and VF modes.	98
Figure 5.6 Mean values of indices under JM, EM, and VF modes: (a) task completion time index; (b) controller effort index; (c) total distance travelled by manipulator end-effector index.	99
Figure 5.7 Typical Q-Q plots of (a) task completion times, and (b) position errors, in Task B and under VF scheme.	101
Figure 5.8 Results of qualitative study under VF scheme.	102
Figure 5.9 Position error at the haptic implement and manipulator end-effector, given the same task as in Figure 2.2b and under different speeds. The tests are conducted using VF scheme.....	104
Figure 5.10 Desired and actual positions of slave manipulator end-effector.	106
Figure 5.11 Unit vector of operator's hand velocity and haptic augmentation force	106
Figure 5.12 Augmented virtual fixture scheme.	107
Figure 5.13 Block diagram of augmented virtual fixture scheme.	108
Figure 5.14 Typical test trajectories of slave hydraulic manipulator end-effector, shown in Figure 2.2, and under (a) virtual fixture mode, and (b) augmented virtual fixture mode.	110
Figure 5.15 Mean values of position errors at master haptic device implement.	112
Figure 5.16 Mean values of position errors at slave manipulator end-effector.	112
Figure 5.17 Task completion times.....	113
Figure 6.1 Block diagram of force augmentation scheme when teleoperated system works under a delayed/lossy network.....	118
Figure 6.2 General architecture of tested telemanipulator. Solid and dashed lines show physical and logical connections, respectively.	118
Figure 6.3 Typical trajectory of hydraulic manipulator end-effector for scenario S4 (TD=400 ms and PL=75%). Subscripts 'm' and 's' indicate displacements of master and slave, respectively.	121

Figure 6.4 Position error at the slave end-effector, operator's hand speed and haptic force, for test shown in Figure 6.3.	122
Figure 6.5 Trajectory of slave end-effector for test S13 (TD=1300 ms; PL=0%).	123
Figure 6.6 Packet losses generated in scenarios S17 and S18.	123
Figure 6.7 Typical trajectory of slave end-effector for scenario S17.	125
Figure 6.8 Typical trajectory of manipulator end-effector for scenario S18.	126
Figure 6.9 Mean values of position errors, task completion times, and operator's hand speeds without force ($\blacktriangle$) and with force ($\bullet$), for all 20 scenarios.	127
Figure 7.1 Typical packet loss for unobstructed ($n=2.0$) and obstructed ($n=3.0$) scenarios.	131
Figure 7.2 Displacement of platform top plate over a 100-second period.	132
Figure 7.3 Actuator displacements of 6-DOF Stewart platform.	132
Figure 7.4 Maintenance tasks used to evaluate performances.	134
Figure 7.5 Typical trajectory of slave manipulator end-effector under force augmentation mode: (a) along x_0^s , y_0^s and z_0^s axes; (b) 3D view; (c) radial position error of slave end-effector.	135
Figure 7.6 Typical trajectory of slave manipulator end-effector under no force mode: (a) along x_0^s , y_0^s and z_0^s axes; (b) 3D view; (c) radial position error of slave end-effector..	136
Figure 7.7 Slave end-effector displacements for Task A over 48(trials) $\times$ 2(schemes)=96 trial runs.	137
Figure 7.8 Slave end-effector displacements for Task B over 96 trial runs.	137
Figure 7.9 Completion times for Task A over 96 trial runs.	139
Figure 7.10 Completion times for Task B over 96 trial runs.	139

LIST OF TABLES

Table 3.1 Parameters used in simulation of the hydraulic actuator.	32
Table 3.2 Specifications of Kodiak 1000 hydraulic manipulator and Stewart platform. .	39
Table 4.1 Network variables used in experiments: one-way delay (TD) and packet loss rate (PL)..	51
Table 4.2. General wireless simulation parameters.	70
Table 4.3 Lookup table of network parameters for hydraulic actuator.....	78
Table 4.4 Characteristics of network scenarios. A, M, and U show that scenario belongs to Acceptable, Marginal, and Unacceptable regions, respectively.	80
Table 4.5 Qualitative summary of time delay and packet drop effects on performance, dedicated channel.....	87
Table 4.6 Qualitative summary wireless network setting effects on performance of system.	87
Table 5.1 Statistical indices for typical tasks based on task completion time (TT) and position error of manipulator end-effector (PE) using VF scheme.....	100
Table 5.2 Statistical measures of indices in force modes.	113
Table 6.1 Characteristics of dedicated networks used in first set of experiments.	120
Table 6.2 Parameters used to emulate wireless channel using NS2 under wireless channel.	124
Table 7.1 Parameters used to emulate wireless channel.	130
Table 7.2 Performance measures under no force (NF) and force augmentation (AU) modes.	138
Table 7.3 Statistical indices for Tasks A and B based on task completion time (TT) and displacement of manipulator end-effector (DE) under two force modes	140

NOMENCLATURE

$x_m, \dot{x}_m, \ddot{x}_m$	Displacement, velocity, and acceleration of the haptic device (Master)	[m], [m/s], [m/s ²]
$x_s, \dot{x}_s, \ddot{x}_s$	Displacement, velocity, and acceleration of the hydraulic actuator (Slave)	[m], [m/s], [m/s ²]
x^*	Delayed version of displacement	[m], [mm]
$x_v, \dot{x}_v$	Displacement and velocity of the valve spool	[m], [m/s]
x_e	Environment displacement	[m], [m/s]
F_m	Force generated by the master manipulator based on a control law	[N]
F_h	Force generated by the operator	[N]
F_e	Interaction force	[N]
F_f	Friction force	[N]
F_b	Backdrive friction force	[N]
F^*	Delayed version of force	[N]
u	Control signal applied to the valve	[V]
m_m	Combined inertia of the master manipulator and the operator's arm	[kg]
m_s	Combined inertia of the piston, actuator rod and load of hydraulic actuator	[kg]
k_d	Combined viscous coefficient of the master manipulator and the operator's arm	[Ns/m]
k_h	Combined stiffness of the operator's arm and the haptic device	[N/m]
P_s	Supply pressure	[Pa]
P_r	Tank pressure	[Pa]
P_1, P_2	Left (or right) actuator chamber pressure	[Pa]
P_L	Differential or load pressure	[Pa]
A	Piston annulus area	[m ²]
d	Equivalent viscous damping coefficient	[Ns/m]
L	Actuator stroke	[m]
Q_1, Q_2	Flows into and out of the actuator chambers	[m ³ /s]
$\bar{V}_1, \bar{V}_2$	Volume of fluid in connecting lines	[m ³]
k_s	Stiffness of the environment	[N/m]
K_v	Servovalve flow gain	[m ^{3/2} / kg ^{1/2}]
ω_v	Natural frequency	[1/s]

ζ_v	Valve damping ratio	
v_{th}	Velocity threshold	[m/s]
c_d	Orifice coefficient of discharge	
ρ	Hydraulic fluid density	[kg/m ³]
k_v	Valve spool position gain	[m/V]
P_e^s	Position of manipulator end-effector	[m]
P_t^m	Position of haptic device	[m]
θ_i^s	Joint angles of slave manipulator	[rad]
θ_i^m	Joint angles of master device	[rad]
α_s	Mapping factor	
G_m, G_s	Impedance of master and slave	[N/m], [Ns/m]
H_m, H_s	Admittance of master and slave	[m/N], [m/Ns]
l_i	manipulator's link length	[mm]
D	Position vector of Stewart top plate	
R	Orientation matrix of Stewart top plate	
L_i	Length of Stewart actuators	[mm]
a	Top plate, short side	[mm]
b	Top plate, long side	[mm]
c	Bottom plate, short side	[mm]
d	Bottom plate, long side	[mm]
H_b	Joint distance from bottom plate	[mm]
H_t	Joint distance from top plate	[mm]
$\vec{F}_{VF}$	Virtual fixture force vector	
$\vec{F}_{AU}$	Augmentation force vector	
$\vec{F}_{AVF}$	Augmented virtual fixture force vector	
$\vec{E}_i^m$	Position error vector at master site	
$\vec{E}_e^s$	Position error vector at slave site	
n	Path loss exponent	[dB]
d_0	Reference distance	[m]
P_r	Received power	[dB]
P_t	Transmitter antenna power	[dB]
P_{min}	Minimum received power level	[dB]
G_r	Receiver antenna gain	[dBi]
G_t	Transmitter antenna gain	[dBi]
X_σ	Gaussian random variable	[dB]

$\{x_R, y_R, z_R\}$	Reference coordinate
$\{x_i^m, y_i^m, z_i^m\}$	Coordinate system of master
$\{x_e^s, y_e^s, z_e^s\}$	Coordinate system of slave
$\{x_0^m, y_0^m, z_0^m\}$	Fixed (global) coordinate system of master
$\{x_0^s, y_0^s, z_0^s\}$	Fixed (global) coordinate system of slave
$\{X^t, Y^t, Z^t\}$	Stewart top frame
$\{X^b, Y^b, Z^b\}$	Stewart bottom frame
<i>GVF</i>	Guidance virtual fixture
<i>FRVF</i>	Forbidden region virtual fixture
<i>WANem</i>	Wide Area Network emulator
<i>NS2</i>	Network simulator version 2
<i>UDP</i>	User data protocol
<i>TCP</i>	Transmission control protocol
T_f	Forward time delay
T_b	Backward time delay
<i>DOF</i>	Degree of freedom
<i>RMS</i>	Root mean square
<i>FFT</i>	Fast Fourier transform
<i>FR</i>	Force reflection scheme
<i>PE</i>	Position error scheme
<i>FP</i>	Combined force reflection and position error scheme (hybrid)
<i>FC</i>	Four channels
<i>TD</i>	Time delay
<i>PL</i>	Packet loss

CHAPTER 1

INTRODUCTION

1.1. Statement of the Problem

This thesis investigates how to enable a hydraulic manipulator, with base excitation, to operate wirelessly using the concept of haptic-enabled teleoperation. The application is towards the utilization of hydraulic manipulators to perform hazardous and/or difficult tasks remotely. More specifically, the targeted application, in this study, is live transmission line maintenance operation [1]. Maintenance of an overhead power distribution system is not easy; especially in places with severe climate conditions preventing human exposure over long period. Therefore, the use of teleoperation approach, in which the operator is removed from direct operation, is helpful to increase the operator's safety, as well as reduce risks and hazards [2].

A teleoperated robotic system is generally composed of: (i) master site, where an operator utilizes a hand-controller to guide the remote manipulator, (ii) slave site, in which a manipulator emulates the behavior of the master hand-controller, (iii) communication channel which connects both slave and master sites, and (iv) feedback

control system. The information (position, velocity, or interaction force) between the master site and the slave site is exchanged through a communication channel. If only information of the master is transmitted to the slave site, the teleoperated system is called unilateral. If the slave manipulator also reflects some information back to the master, by using feedbacks, the system is bilateral [3].

Three main issues related to general teleoperation of base-excited manipulators are:

- (i) Designing feedback control systems needs to consider the challenges when the slave manipulator interacts (constrained motion), or is not in contact (free motion), with the environment. With respect to the position tracking at the slave site, the hydraulic manipulator at the slave site could start lagging (stay behind the master motion) depending on the configuration of the slave robot, responsiveness of the hydraulic actuators, or quality of the communication channel connecting master and slave sites.
- (ii) The quality of communication channel, and therefore performance of the teleoperated system, is influenced by the network variables such as time delay and packet loss. For instance, in a delayed system, the operator perceives the information of slave site some time later than the actual interaction, and the commands, sent by the operator to the slave, are transmitted with a delay too. Thus, the presence of time delay affects the performance of a delayed system. Achieving a transparent and stable haptic-enabled teleoperated system to control a hydraulic manipulator, through a delayed and lossy communication channel, is an issue which should be studied. Furthermore, variables of a wireless network, that affects the performance, should be studied.

- (iii) With respect to the application in this study, the manipulator is placed on top of a crane, and is therefore subject to unwanted motion due to wind gust, reaction forces, unstable soil, and compliance in the crane actuation. When the manipulator base is excited, the difficulty in performing tasks naturally increases.

1.2. Objectives of the Research

The objectives of the current study are:

- (i) To design a feedback control system in order to reduce the position error between the master device implement and the slave manipulator end-effector in both unilateral and bilateral modes of operating a hydraulic manipulator to perform live-line maintenance.
- (ii) To investigate the effects of communication channel variables on the performance of teleoperated base-excited hydraulic manipulators. The network variables can be constant (as in a dedicated network), or time-varying (as in a wireless channel).
- (iii) To implement the above developments for manipulators performing live transmission line maintenance.

In order to achieve the above objectives, three research questions are to be addressed:

- (i) How do various types of hand-controllers and mapping systems (joint mapping and end-effector mapping) affect the performance of a unilaterally-controlled teleoperated manipulator?

- (ii) How to design and employ force feedback schemes in order to bilaterally enhance the control of hydraulic telemanipulators by reducing position errors between the master device implement and the slave manipulator end-effector?
- (iii) How to emulate dedicated and wireless communication channels offering repeatable experiments, realistic test results, and consistent network parameters across trials? And, how to alleviate the effect of a communication channel on the performance of a teleoperated hydraulic manipulator?
- (iv) How does the excitation of the slave manipulator base influence the otherwise well-performing teleoperated system?

1.3. Scope of the Research

This research is built upon the previous work done at the University of Manitoba [4], where the concept of virtual fixture was used to unilaterally control a hydraulic manipulator to perform live-line maintenance tasks. In the current research, the available teleoperated hydraulic manipulator is retrofitted to include a Stewart platform to simulate motion of the crane bucket in live-line maintenance. It is also controlled bilaterally, by a haptic device, while it operates under either a dedicated or a wireless communication channel.

Two main issues in teleoperated hydraulic systems are stability and transparency, especially when the telemanipulator is controlled through a delayed and lossy communication channel. Firstly, the overall closed-loop system should be stable irrespective of input commands or type of environment [3]. Secondly, a feel of performing task at the remote site must be available to the operator. Technically, this is

achieved if position tracking and force tracking are both faithful [5]. Many research studies have addressed the tradeoff between transparency and stability for electrically-actuated manipulators with controllable torques (see [6] and the references cited therein). As compared to the class of electrically-actuated robots, research on application of bilateral control, applied to the class of hydraulic manipulators, is sparse. Although there exist some studies referring to transparency of the control of hydraulic manipulators including nonlinear dynamics of hydraulic functions and the operator's dynamics [2, 7, 8, 9, 10, 11, 12, 13], none of them investigated the transparency of such manipulators when they were controlled through a wireless channel.

The research is conducted using experiments on two teleoperated hydraulic systems: a double-rod valve-controlled hydraulic actuator and an industrial hydraulic manipulator. The hydraulic teleoperated actuator is composed of an Omni Desktop haptic device (master) and a valve-controlled hydraulic actuator (slave). The hydraulic telemanipulator comprises a PHANTOM Desktop haptic device (master site) and a 4-degree of freedom (DOF) slave Kodiak hydraulic manipulator placed on a 6-DOF Stewart platform. The second platform is an excellent training simulator for linemen to become familiar with real conditions of performing live-line maintenance tasks using the telerobotic technology. Both master and slave sites are connected through a channel generated by either the Wide Area Network emulator (WANem) or the Network Simulator version 2 (NS2) [14]. The NS2 generates various network topologies, protocols, and network traffic patterns in emulation mode [15].

With respect to the transparency of hydraulic telemanipulators, extensive experimental studies are conducted. The first study investigates the effectiveness of two hand-

controllers (a conventional seven-function joystick and a PHANTOM Desktop haptic device) on the performance of unilaterally-controlled hydraulic telemanipulators that can also incorporate the concept of the virtual fixture. Results of this study show how the use of haptic device, utilizing the concept of virtual fixtures, affects position errors at the slave end-effector and the task completion time. In controlling hydraulic telemanipulators using the concept of virtual fixtures, some problems are inevitable. Virtual fixtures cannot satisfactorily reduce the position error at the slave manipulator end-effector; but, they decrease position errors originated from unwanted hand motions at the master device implement. Unilateral control, however, does not provide any feeling about what occurs at the slave site.

Specific to this study, the position error between the slave manipulator and the master device can potentially increase when the operator moves faster along a predefined virtual fixture trajectory, or when the slave and master sites are connected through a delayed and/or lossy network. The position inaccuracy can be dealt by designing a force augmentation scheme that is able to alert the operator when the position error appears at the slave end-effector.

The effect of delayed and lossy communication channels on the performance of teleoperated hydraulic actuators is investigated while the teleoperated system is augmented by several bilateral control schemes. Results are employed to construct a set of performance charts describing the quality of position tracking of the slave actuator and force tracking of the haptic device. Finally, the transparency of a base-excited hydraulic telemanipulator is investigated when it is controlled through a wireless network, and

augmented by the force augmentation scheme. The base of the slave manipulator is excited by a motion platform simulating motions of a crane bucket.

1.4. Thesis Outline

Detailed literature review is presented in Chapter 2 on the haptic-enabled teleoperation of hydraulic manipulators which includes describing application area of interest as well as general background on teleoperation and haptics interaction, communication between master and slave, and moving base telemanipulators.

In Chapter 3, the experimental setups are described. The test rigs are: (i) a double-rod valve-controlled hydraulic actuator, developed to observe the effect of network quality on transparency and stability of bilaterally controlled single hydraulic actuator, and (ii) a hydraulic telemanipulator, installed on a moving platform, for performing live-line maintenance tasks.

Chapter 4 presents a comparative study of four schemes for bilateral control applied to a hydraulic actuator working under either a dedicated or a wireless communication channel. The schemes evaluated, are position error, force reflection, combined force reflection and position error, and four channels. The goal is to investigate how well a teleoperated hydraulic manipulator operates under delayed and lossy communication channels. This chapter establishes a technique to construct performance charts for effective control in a wireless environment.

In Chapter 5, the performance evaluation of a teleoperated hydraulic manipulator performing live-line maintenance tasks is investigated. More specifically, this section investigates the effectiveness of the use of virtual fixture, followed by alleviating the

weakness of using virtual fixtures: induced poor position tracking at the slave end-effector, which is done by proposing a position referenced force augmentation scheme. The scheme helps to reduce position errors at the slave end-effector.

Chapter 6 shows how the force augmentation scheme is employed to reduce slave position errors due to the existence of a delayed and/or lossy communication channel. Experimental validations are performed with the communication channel emulating the behavior of either a dedicated or a wireless network.

In Chapter 7, the controls of the slave hydraulic manipulator through a wireless channel is examined when the manipulator base is excited by a motion base to reflect possible disturbances arising from the motion of the manipulator base in the real field. Contributions made in this thesis and suggestions for future work are provided in Chapter 8.

CHAPTER 2

RELEVANT BACKGROUND

2.1. Application Area of Interest

In this chapter, a review of the literature on topics related to wireless control of manipulators is presented. The application, targeted in this thesis, is the live-line maintenance using hydraulic manipulators. Live-line maintenance can be performed for different reasons such as changing an insulator, replacement of damaged section of a conductor, testing the insulator, and transferring a conductor to a higher pole. In live-line maintenance, it is essential that the power transmission system be always available [16]. At the same time, maintenance of an overhead power distribution system is a difficult task to perform, especially in places with harsh climate conditions preventing human exposure over a long period of time. Therefore, live-line maintenance workers (linemen) need a high level of expertise. On the other hand, appropriate techniques should be chosen to increase safety and convenience, and to decrease hazards and risks. Figure 2.1 shows how a lineman uses the live-line equipment to perform maintenance tasks.

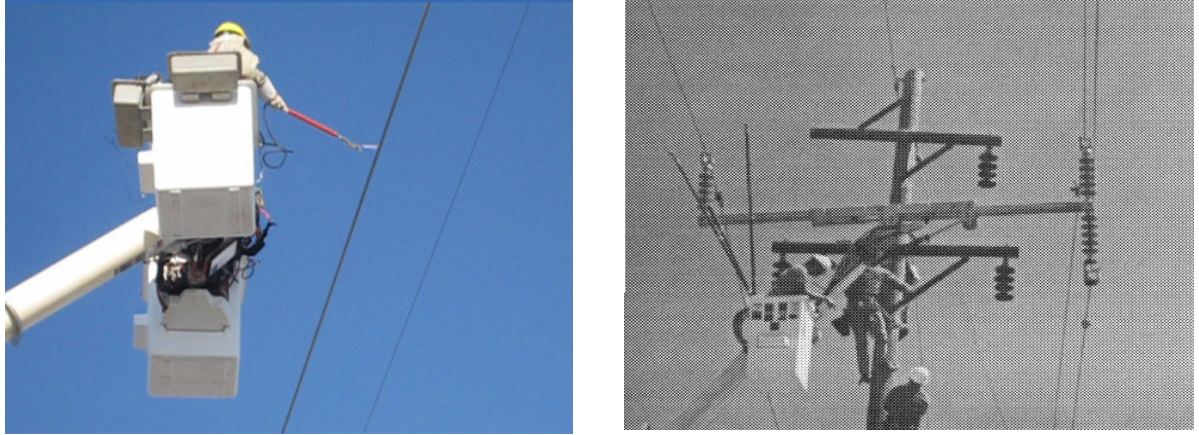


Figure 2.1 Conducting live-line maintenance near energized lines.

Five typical tasks in live-line maintenance are shown in Figure 2.2. These tasks are performed manually by operators working in a location above the ground and near high voltage power lines. As observed, these tasks are performed by using an insulated pole (hot-stick) which is normally made of fiberglass. The tasks are: pulling out a cotter pin (Task A), loosening or tightening a nut (Task B), connecting or disconnecting a ball and socket joint (Task C), inserting a cotter pin (Task D), and twisting a tie wire around an electrical cable (Task E). As illustrated, the cotter pin prevents the ball and socket joint to be disconnected (see Figure 2.2d). Therefore, in a practical sequence, this task should be performed prior to disconnecting a joint (Task C). Figure 2.2b depicts the circular path used for loosening or tightening a nut. To disconnect or re-connect a ball and socket joint, which is depicted in Figure 2.2c, a combination of several straight lines is expected to be followed by the operator. Figure 2.2d shows how a cotter pin can be inserted back in place to secure the ball and socket joint. Figure 2.2e shows how a wire is twisted around a cable.

The combination of defined tasks can also be used to perform a complete maintenance task in the test station. For instance, to change a broken insulator, a combination of Tasks

(A), (C), and (D) can be used. In other words, the cotter pin is pulled out (Task A), the joint is disconnected (Task C), followed by changing the insulator. Afterward, the joint is re-connected (Task C), and the pin is inserted back by hammering (Task D).

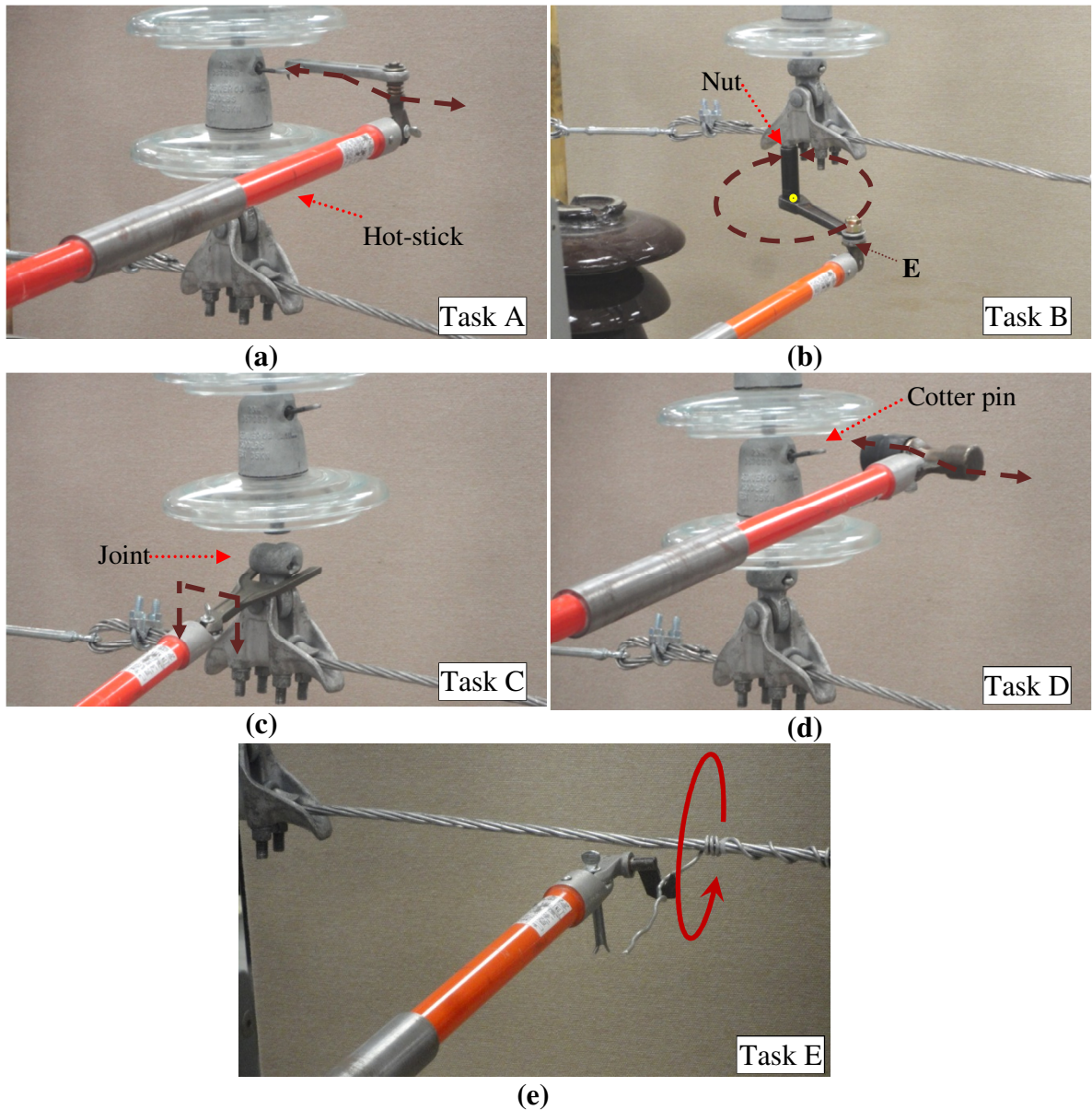


Figure 2.2 Typical maintenance tasks: **(a)** Task A: pulling out a cotter pin; **(b)** Task B: loosening or tightening a nut; **(c)** Task C: connecting or disconnecting a ball and socket joint; **(d)** Task D: inserting a cotter pin; **(e)** Task E: twisting a tie wire around cable.

Some ways that help linemen avoid considerable hazards and risks are [17]:

- (i) Employing live-line tools, such as hot-stick, which keep linemen at appropriate distance from the energized equipment, and insulating gloves which electrically protect linemen when working directly with live parts.
- (ii) Using hovering helicopters or live-line trucks by which the lineman can access energized lines at a distance.
- (iii) Implementing the potential technique which keeps the lineman at the same voltage as the transmission line.
- (iv) Using the concept of teleoperation, in which linemen remotely control a slave manipulator mounted on a truck.

This research focuses on conducting live-line maintenance using robotics technology whereby a manipulator is installed on top of a live-line truck to perform tasks using a hot-stick, *i.e.* combining approaches (i), (ii) and (iv). The concept is portrayed in Figure 2.3 in which a hot-stick and an associated tools are attached to the end-effector of a robotic arm. The manipulator is then remotely controlled by a lineman (teleoperation) to perform live-line tasks. The teleoperated manipulator enables the operator to perform typical live-line maintenance tasks at a distance. It can also be used to train linemen how to safely work with maintenance tools attached to the robot end-effector. In development of this test rig, shown in Figure 2.3, three issues need to be investigated to practically be able to perform maintenance tasks at a distance. They are listed below:

- (i) Haptic-enabled teleoperation (unilateral or bilateral) of hydraulic manipulators, and the use of force feedback to help the operators perceive how well the system operates; and therefore, to enhance the performance.

- (ii) Wireless communication between master and slave sites.
- (iii) Investigating effects of the base movement to reflect real conditions of the slave manipulator when it is mounted on top of a crane bucket.

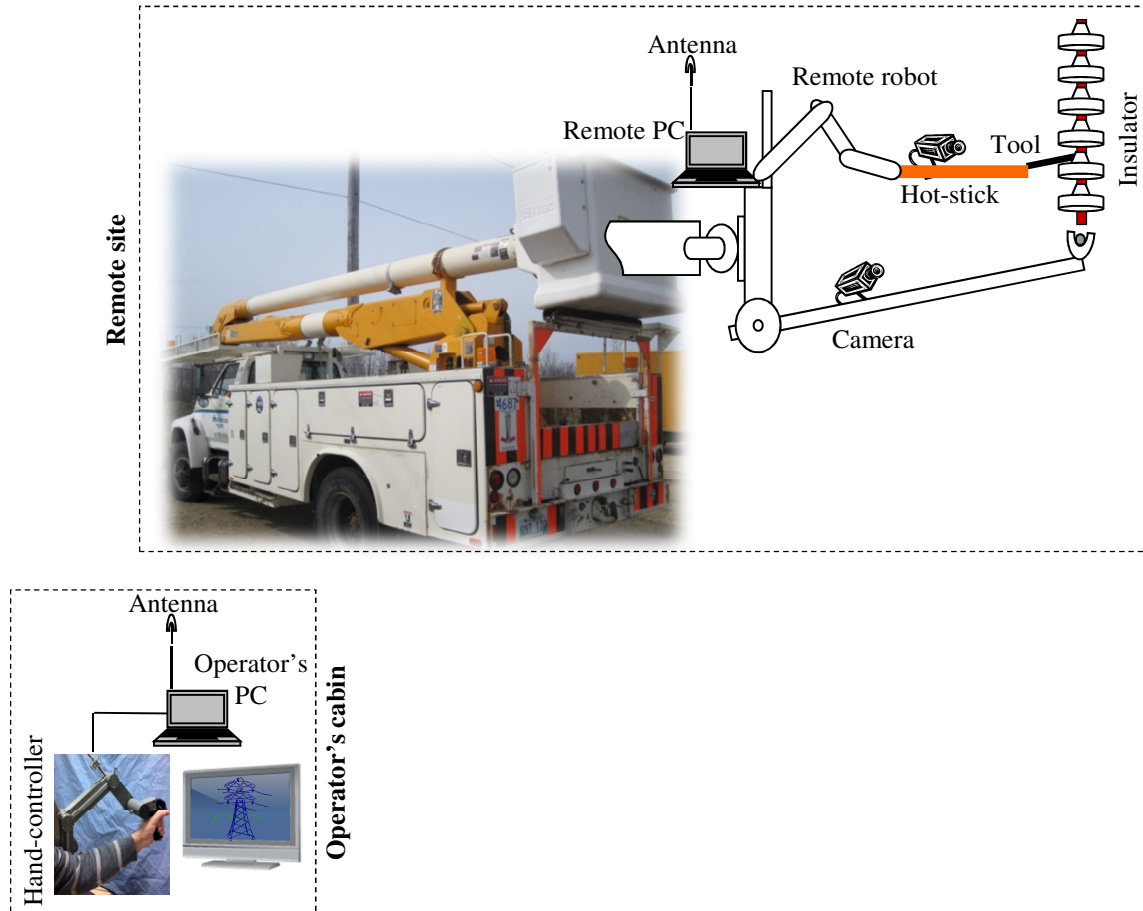


Figure 2.3 Concept developed to perform live-line maintenance near energized lines. A lineman uses a hand-controller to control manipulator at a distance.

The use of robotic systems in live power line maintenance possesses some advantages such as increasing the linemen's safety, and allowing them to combine the accuracy and good performance of the system with the operator's intelligence [18, 19]. In spite of these advantages, the adoption of robotics technology in live-line maintenance is still new, and introduces challenges that need investigation. Within the context of robotics technology

applied to live transmission line maintenance, Toussaint *et al.* [1] presented numerous initiatives which have been undertaken to develop robots for transmission line maintenance including different robotic technologies which have been developed at Hydro-Quebec's research institute (IREQ) since 1998. Montambault and Pouliot [19] presented a literature review of innovative devices applied to live transmission line maintenance. Tsukahara *et al.* [20] formulated a conceptual design for a power distribution line maintenance robotic system using a computer graphic simulator as well as an experimental robotic system capable of performing tasks using task-level instructions. Aracil *et al.* [21] developed a teleoperated system for live-line maintenance, which executes tasks directly on hot lines using a master arm. Takaoka *et al.* [18] extended a robotic system for executing routine jobs automatically. Lu *et al.* [22] developed a live working robot with local automatic and master-slave operation possibilities. None of the above studies focused on wireless control of teleoperated system, or investigated effects of crane bucket motions.

2.2. Review of Teleoperated Systems

The prefix “tele” means at a distance, and teleoperation induces any controllable operation of a system at a distance [3]. In a teleoperated system, the operator controls the master device, then communication channel transfers position, velocity, or force information to the slave site, and the slave machine interacts with the environment (see Figure 2.4). Figure 2.5a and Figure 2.5b illustrate how information flows between master and slave sites in unilateral and bilateral controls, respectively.

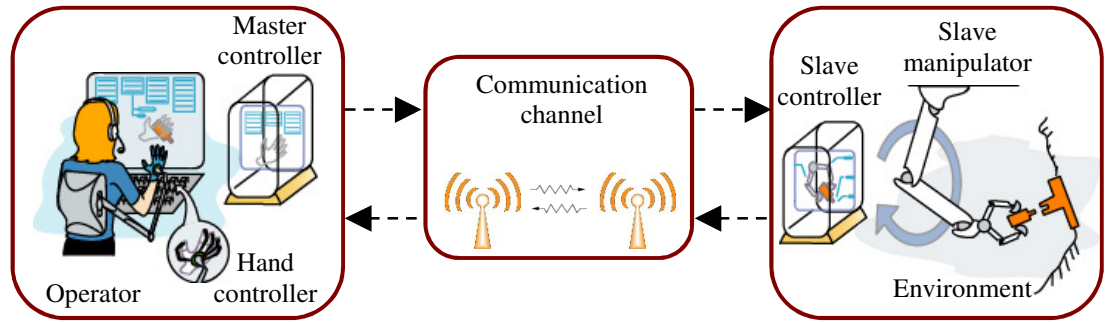


Figure 2.4 Elements of a teleoperated system. Dashed arrows indicate the direction of information flow.

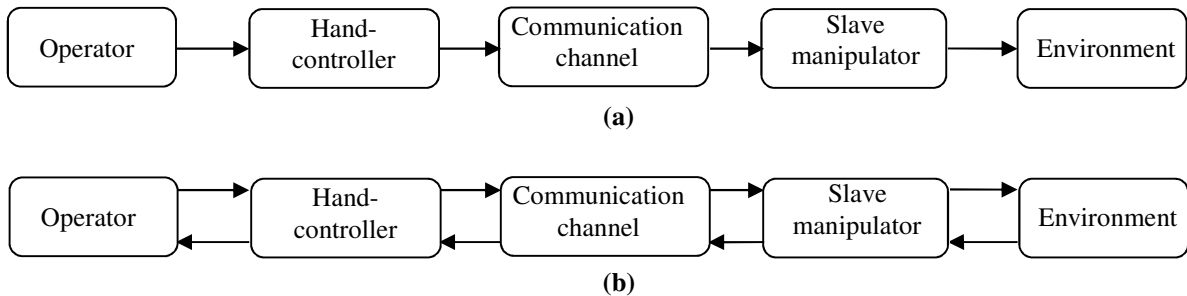


Figure 2.5 (a) Unilateral and (b) bilateral teleoperated systems.

2.3. Haptic-Enabled Teleoperation: Concept

2.3.1. Definition

A slave manipulator is a device, *e.g.* a robotic arm, which is remotely controlled by an operator using a hand-controller device. Operators use typically visual information, directly or through cameras, to perform a task. The hand-controller is called a “haptic” device if it is capable of producing force. When kinematic and/or dynamic information (such as position, velocity, force or torque) of slave site is transferred into the haptic device, a sense of telepresence is provided to the operator. Indeed, telepresence is the operator’s feeling about the slave site of a teleoperated system [5]. In some applications of teleoperated systems, haptic feedback alone has been shown to be more valuable than

visual feedback [23, 24, 25, 26]. Haptic interfaces have been used in wide variety of applications such as hazardous material handling in nuclear services [27], medical robotics, tele-ultrasound, and tele-surgery [28, 29, 30, 31, 32, 33], underwater robotics [34], mobile robots [35, 36, 37, 38], and micro-manipulation and assembly [39].

Haptic interaction is one of fundamental and effective ways by which the operator can perceive changes in the working environment. Haptic interaction can provide an additional link, particularly when the hand-controller is configured in a spatially intuitive way [10]. When the assigned task implies a contact with the environment (force control) or the operator needs to follow particular path (position control), having an additional perception of interaction force or position error helps the operator feel how efficiently the teleoperated system operates. The advantage of the position control is that the slave manipulator mimics the operator's motion [2].

Many industrial machines require extensive use of hydraulics [13]. The application of haptics in teleoperated hydraulic systems is extensively described in [4]. The research activities in the area of haptic control of hydraulic manipulators are limited to a few studies [7, 9, 8, 10, 11, 13]. Kontz *et al.* [10] showed that by shaping the impedance, a teleoperated excavator provides a better “feel” of telepresence to operators. This concept was evaluated in a human-in-the-loop test-bed [12]. The force feedback was generated using a virtual spring which couples the displacement of the haptic device to the displacement of a crane bucket, *i.e.*, the force feedback is proportional to the position error between the master device and the slave manipulator. Kontz and Book [2] also employed a hybrid position/rate haptic control for a hydraulically-actuated lifter, and showed the advantages of employing rate-mode control for moving the forklift around,

and position-mode control for controlling the implement. Haptic control of excavators has also been explored by Parker *et al.* [8] and Lawrence *et al.* [11] who developed a magnetically-levitated joystick with stiffness feedback to control a 4-DOF hydraulic excavator. Indeed, the joystick stiffness was mapped into the end-effector force and the joystick position was mapped to end-effector velocity. Zarei-nia *et al.* [13] experimentally compared the performance of a number of bilateral control schemes, previously used for electromechanical systems, to a hydraulic actuator.

2.3.2. Master position referenced force

In teleoperation applications where the position control of the slave manipulator is important, feeling position errors by the operator was shown as a way to reduce errors at either the master device or the slave manipulator [40]. A commonly-used haptic force is the one that is built upon the position error at the master device implement (that is also called virtual fixture) or the slave manipulator end-effector. The term “virtual fixture” refers to a general class of guidance modes that help a robotic manipulator perform a task by limiting its movement into restricted regions (forbidden region virtual fixture: FRVF) or influencing its movement along desired paths (guidance virtual fixtures: GVF). Virtual fixture is an overlay of abstract sensory information on a workspace in order to improve the telepresence of a remotely manipulated task. The concept of virtual fixtures was first introduced by Rosenberg [41]. To understand what a virtual fixture is, an analogy with a real physical fixture such as a ruler is often used [41]. A simple task such as drawing a straight line on a piece of paper on free-hand is a task that humans are normally unable to perform with good accuracy and high speed. However, the use of a simple device such as

a ruler allows the task to be carried out fast and with good accuracy. The use of a ruler helps the user guide the pen along the ruler, and reduces the operator's mental load, thus increases the quality of the task [4].

There are many advantages in using virtual fixtures in telemanipulation such as interacting with the user and not with the task environment, existence of no mechanical constraint, no need for machining or maintenance, easy prototyping and modifying, designable in many forms such as damped surfaces, frictional contacts, attractive/repulsive fields, or compliant surfaces [4]. Rosenberg [41] argues that the success of virtual fixtures is not only because the user is guided by the fixture, but that the user experiences a greater presence and better localization in the remote workspace. However, in the context of human-machine collaborative systems, the term "virtual fixtures" is often used to refer to a task dependent aid that guides the operator's motion along desired directions (GVF) while preventing motion in undesired directions or regions of the workspace (FRVF) [4]. When there are some regions at the remote site which should be prohibited for the manipulator end-effector to fall into, the forbidden regions can be defined at various regions. Thus, FRVFs prevent the operator from issuing commands that can result in the manipulation system ending up in such a region.

2.3.3. Slave position referenced force

In the context of haptic forces that are generated based on the position error at the slave site, there have been a few studies that focused on producing the haptic force using slave position error. In all of these studies, positions of the haptic device (master) and the hydraulic manipulator (slave) provided a reference position to each other which resulted

in applying a haptic force to the operator's hand [13, 42]. Kontz *et al.* [10] proposed a scheme commanding the haptic device to generate a force that couples the motion of the haptic device to the excavator bucket movement. Hayn *et al.* [43] implemented a similar concept to operate a hydraulic excavator. Ahn *et al.* [40] proposed a compliance control scheme for the position referenced bilateral control system, in which the position difference between the master implement and the slave end-effector is treated as an equivalent contact force. In these studies, the produced haptic force was parallel to, and in proportion with, the position error vector at the slave end-effector. The generated force indicates to the operator of the slave status, *i.e.* whether it is moving ahead or behind the intended desired trajectory, by pulling towards, or pushing against, the operator's hand.

2.3.4. Impedance vs. admittance

In general, position referenced feedback systems, *e.g.* virtual fixtures, are categorized into admittance-type and impedance-type [44]. To clarify the concept of admittance-type and impedance-type systems, consider the teleoperated system depicted in Figure 2.6. In this system, F_h and F_e are the operator's force and the environment interaction force, respectively. x_h represents the operator's displacement, and the environment displacement is depicted by x_e . With reference to Figure 2.6, impedances of master and slave sites are described, respectively, as follows:

$$G_m = \frac{F_h}{x_h} \quad (2.1)$$

$$G_s = \frac{F_e}{x_e} \quad (2.2)$$

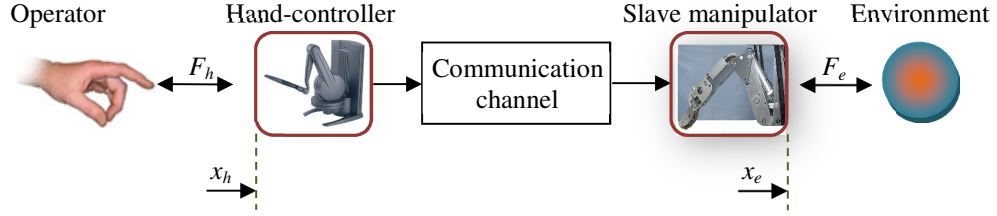


Figure 2.6 Sign convention in admittance-type and impedance-type teleoperated systems.

where G_m and G_s are referred to the impedance of master and slave sites, respectively.

Similarly, admittances at the master site (H_m) and slave site (H_s) are defined as follows:

$$H_m = \frac{x_h}{F_h} \quad (2.3)$$

$$H_s = \frac{x_e}{F_e} \quad (2.4)$$

An impedance-type virtual fixture, for example, is graphically described in Figure 2.7. As observed, the force generated by the haptic device is computed based on the distance between actual position of the master implement, $\vec{P}_a = [x_a \quad y_a \quad z_a]^T$, and desired position of the implement, $\vec{P}_d = [x_d \quad y_d \quad z_d]^T$. The force can be generated based on the Hooke's law, for instance, as follows:

$$\vec{F} = -G_{VF}\vec{E} \quad (2.5)$$

where $F = [F_x \quad F_y \quad F_z]^T$ represents the force vector applied to the operator's hand along the reference coordinate system $\{x_R \ y_R \ z_R\}$, respectively. G_{VF} is the impedance of the virtual fixture, and in a simple (scalar) form is the stiffness of the virtual spring pulling the operator's hand toward the desired trajectory. The haptic end-effector position error, $\vec{E}$, is defined as:

$$\vec{E} = \begin{bmatrix} x_a - x_d \\ y_a - y_d \\ z_a - z_d \end{bmatrix} \quad (2.6)$$

With reference to Figure 2.7, when the end-effector is on desired trajectory or on-track, the virtual spring is in rest position ($x_a = x_d, y_a = y_d, z_a = z_d$), *i.e.* no force is generated. However, when operator moves the end-effector out of desired trajectory and penetrates into the forbidden region (off-track), the virtual spring generates a force ($\vec{F}$) which is proportional to the amount of penetration into the forbidden region.

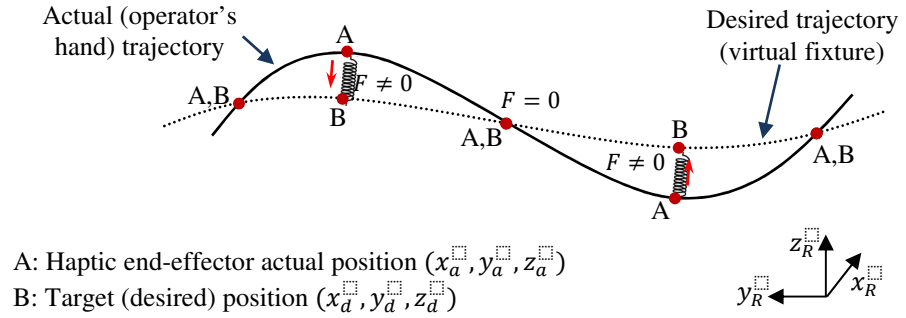


Figure 2.7 Virtual spring pulls operator's hand toward desired trajectory. End-effector position can be on-track ($F = 0$) or off-track ($F \neq 0$).

2.4. Network Quality in Teleoperation

Traditionally, the performance of teleoperated systems is measured through uncontrollable network (*e.g.* the Internet), or over simplified emulated network (*e.g.* constant delay). These methods have some limitations such as unrepeatable experiments, unrealistic test results, and inconsistent network parameters across trials. To overcome these limitations, a computer running a network emulator is used to emulate the communication channel (Figure 2.8). Network emulator is able to delay and drop packets based on the user-defined simulated network scenarios. The main advantage of using

network emulation is to allow the network variables to be specified for generating consistent and controllable network scenarios. By using the same network parameters and random seeds, the network conditions can be replicated for each run of the experiment. For example, by using NS2, different network topologies, protocols, and network traffic patterns can be generated while running under the network emulation mode, which was previously used for constant time delays [15], and time delays that were generated from measurements over the Internet [45].

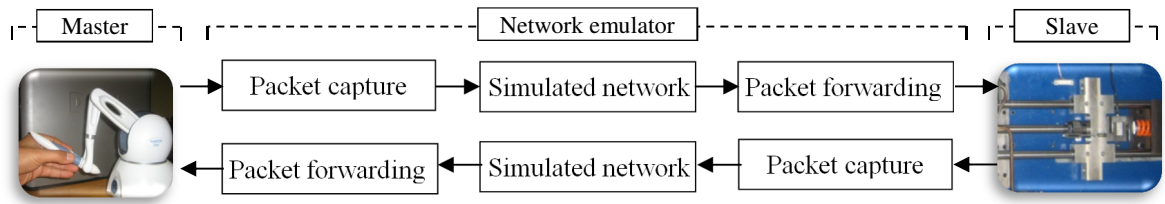


Figure 2.8 Network communication setup between master and slave sites.

Network delay, which is also known as latency, refers to the time it takes for a packet of data to travel across the network from a node to the designated destination. Network delays in communication channel are caused by: (i) processing delay due to processing the packet header by routers; (ii) queuing delay due to the time spent in routing queues; (iii) transmission delay, which is the time spent to push packet's bits into the link; and (iv) propagation delay, which is the time needed for a signal to reach its destination via the physical communication link [42]. When the Internet is used as a communication channel, not only time delay but also other network variables such as packet size, packet loss and packet order affect the entire performance of the networked system. Dropped packets occur when one or multiple data packets fail to reach the predefined destination.

This is caused by channel congestion, data rejection in-transit, faulty network hardware, faulty network drivers or signal attenuation due to the distances between transmitter and receiver, especially in wireless communication [46].

For dedicated channels, constant packet loss and near-constant latency are emulated, while for wireless networks, time-varying packet loss and latency are generated in the communication channel. In wireless channels, information is transmitted by radiating a modulated electromagnetic wave at a certain carrier frequency by means of a transmitter antenna and picking up energy of the radiated wave by means of a receiver antenna [47]. Existence of time-varying delays and packet losses are two phenomena in wireless networks that seriously deteriorate performance and stability of the system [48, 49].

The effect of time delay on the performance of control schemes for a bilateral teleoperated system was first reported by Ferrel [50]. This then led to the development of various control schemes such as scattering transformation [51], wave variable [52], H_∞ robust control [53, 54], shared compliant control [55] and wave variable with prediction [56] for stable and reliable bilateral control systems. Later on, some researchers such as Rodríguez *et al.* [57], Arcara and Melchiorri [58], Guiatni *et al.* [59], Aliaga *et al.* [60] and Aziminejad *et al.* [61] investigated and compared the effectiveness of various schemes towards bilateral control of teleoperated systems. During the early 1960s, several researchers have tried to understand the effects of communication delay in teleoperated systems [62, 63] in which transmitting force feedback to the master site under the effects of delays in communication channel was tested [62].

2.5. Teleoperation of Mobile Manipulators

A mobile robotic system is composed of a manipulator mounted on top of a movable base, and is normally used in unstructured and unknown environments which makes its operation more difficult than in a case where the environment is known [64, 65]. Teleoperation of manipulators with moving base has many promising applications such as live transmission line maintenance, underwater inspection, flight simulators, planets exploration, navigation in hazardous environments, and inspection of industrial constructions [66]. Retrofitting a robotic manipulator with a moving platform increases the working envelope and motion flexibility. When the base motion is undesirable, and originates from disturbing forces and torques, the system is called base-excited system. In live-line maintenance, as an example, the slave manipulator must be installed on top of a crane bucket, and therefore, its base is subject to unwanted excitations due to wind gust or compliance in the boom.

With respect to the teleoperated control of base-excited manipulators, combination of moving platform, slave manipulator, and master hand-controller adds extra degrees of mobility to the system, which in turn creates a kinematically redundant robotic system. Therefore, the control of a manipulator with moving base, under teleoperation mode, becomes more challenging than stationary one which is autonomously controlled.

Most of the studies on teleoperated systems with movable base have focused on ones mounted on wheeled mobile platforms [67, 68, 69]. Research activities in the area of teleoperation of manipulators with mobile base, applied to live-line maintenance, are limited to a few studies which discuss the design and development of new mechanisms for mobile platforms. None of them dealt with investigating the effect of base excitation

of the slave manipulator on performance of the teleoperated system. Toussaint *et al.* [1] presented a comprehensive review of the state of the art which focused on mobile robots designed to cross obstacles along a typical transmission line, while the conductor was used as support for traveling. Song *et al.* [70] developed a mobile robot designed for repairing broken strands in power grid. This robot, consisting of a mobile platform and associated maintenance tools, could move along energized lines and repair broken strands. The robot was tested in a laboratory setting while it was guided by an operator to approach a desired location. Jian *et al.* [71] designed a mobile robot for inspection and maintenance of power transmission lines. The robot was designed as a cable car with two multi-joint arms. Park *et al.* [72] developed a new inspection robot system for suspension insulator strings to detect faulty insulators. The system adopted a wheel-leg moving mechanism that made the robot small and light. Takaoka *et al.* [73] proposed a conceptual design of a robotic station for performing live-line maintenance. In this design, a dual arm manipulator was considered to be installed atop a mobile crane to automatically perform live transmission line maintenance. An operator controlled the operation using the visual feedback system to observe the slave site. The design was validated in a laboratory setting by conducting a single maintenance task: exchanging insulators.

CHAPTER 3

EXPERIMENTAL TEST RIGS AND MODELING

3.1. General Description of the System

Two teleoperated experimental systems are employed in this thesis. The test rigs are: a teleoperated single hydraulic actuator and a 4-DOF teleoperated hydraulic manipulator. The concepts, developed in this thesis, are first examined on the double-rod valve-controlled hydraulic actuator because of its simplicity and safety, and then extended to more complex tasks using the hydraulic manipulator. Figure 3.1 depicts the general architecture of the test rigs. Each system comprises a master device, a network emulator, a slave manipulator, and an environment with which the slave end-effector interacts. In each test rig, the environment and the slave robot may adequately be simulated by software. The network emulator can be implemented by a physical connection or a network emulation software such as Network Simulator Version 2 (NS2) [14] and Wide Area Network emulator (WANem) [42]. The modules in each test rig interface with each other through the User Datagram Protocol (UDP) connections.

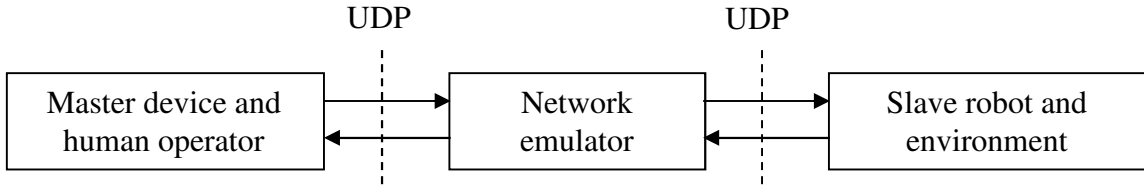


Figure 3.1 General architecture of teleoperated test rig. Dashed lines indicate UDP connection.

3.2. Description of the Sub-Systems

3.2.1. Slave hydraulic actuator

Figure 3.2 shows the single hydraulic actuator setup comprising a PHANToM Omni haptic device that is guided by the operator, and a double-rod valve-controlled hydraulic actuator. The actuator interacts with a linear spring as an environment. The interaction force between the hydraulic actuator and the environment is measured by a force sensor attached to the end-effector. The master PC controls the haptic device. The slave PC, that controls the hydraulic actuator, is equipped with a set of data acquisition boards. The information between the master and the slave is transferred through a dedicated or a wireless communication channel emulated by the WANem or NS2, respectively. Both emulators generate various network scenarios based on controllable parameters of the communication channel such as time delay, packet loss, network topology, and network protocol [74, 42].

Before conducting full experiments, the actual hydraulic actuator (in Figure 3.2) is replaced with its simulation. The hydraulic actuator consists of an electro-hydraulic servovalve and a hydraulic actuator that is in contact with an environment (see Figure 3.3). The control input, u , causes valve spool to move (x_v) which in turn controls flows (Q_1 and Q_2) into and out of the actuator [75].

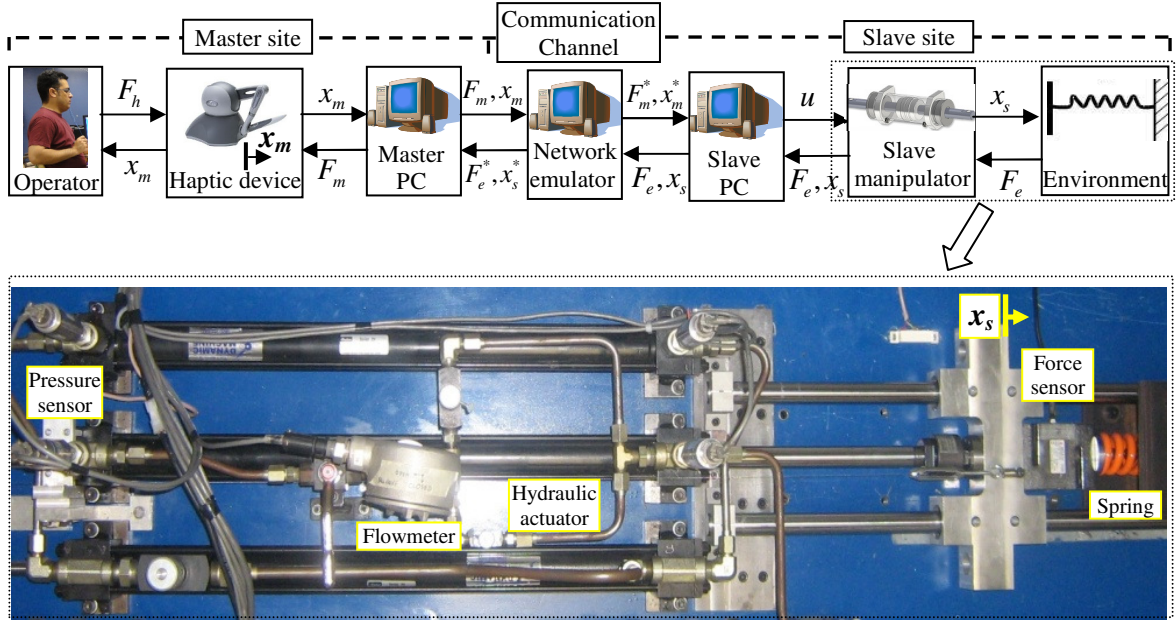


Figure 3.2 Teleoperated hydraulic actuator setup. Subscripts “s” and “m” denote variables at slave and master sites, respectively. The superscript “*” in $x_{s/m}^*$ and $F_{s/m}^*$ denotes a delayed/lossy version of displacement and force.

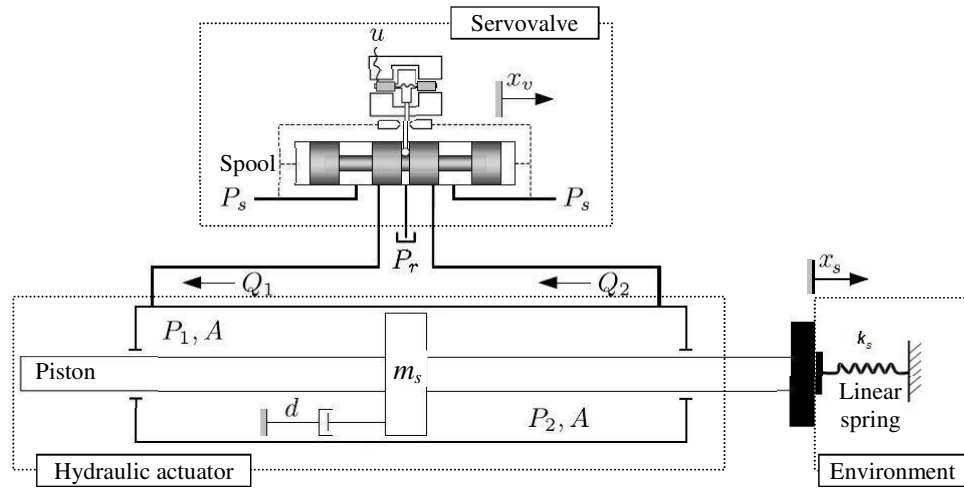


Figure 3.3 Schematics of hydraulic actuator interacting with a stiffness dominant environment.

Assuming the actuator is activated by an ideal critical center servovalve, with matched and symmetrical orifices, the nonlinear governing equations of the flows Q_1 and Q_2 are written in the following compact form [76]:

$$Q_1 = \frac{c_d}{\sqrt{\rho}} w x_v \sqrt{\frac{P_s - P_r}{2} + \text{sgn}(x_v) \left(\frac{P_s + P_r}{2} - P_1 \right)} \quad (3.1)$$

$$Q_2 = \frac{c_d}{\sqrt{\rho}} w x_v \sqrt{\frac{P_s - P_r}{2} + \text{sgn}(x_v) \left(P_2 - \frac{P_s + P_r}{2} \right)} \quad (3.2)$$

where c_d is the orifice coefficient of discharge, and ρ is the hydraulic fluid density. w is the width of the port cut into the valve bushing through which the fluid flows. The supply and tank pressures are denoted by P_s and P_r , respectively. Variables P_1 and P_2 refer to the hydraulic pressures in each of the actuator chamber. The sign function is defined as follows:

$$\text{sgn}(x_v) = \begin{cases} +1 & x_v > 0 \\ 0 & x_v = 0 \\ -1 & x_v < 0 \end{cases} \quad (3.3)$$

The continuity equations describing the pressure changes in each actuator chamber as a function of flows in and out of the actuator, Q_1 and Q_2 , are written as follows [77]:

$$\dot{P}_1 = \frac{\beta_h}{A x_s + \bar{V}_1} (Q_1 - A \dot{x}_s) \quad (3.4)$$

$$\dot{P}_2 = \frac{\beta_h}{A (L - x_s) + \bar{V}_2} (-Q_2 + A \dot{x}_s) \quad (3.5)$$

where A is the annulus area of the piston. The volumes of fluid contained in the connecting lines between the servovalve and the actuator are denoted by $\bar{V}_1$ and $\bar{V}_2$. The actuator stroke is denoted by L . The fluid bulk modulus is given by β_h . x_s and $\dot{x}_s$ are the

displacement and velocity of hydraulic actuator, respectively. The equation of motion for the hydraulic actuator is [77]:

$$AP_L = m_s \ddot{x}_s + d \dot{x}_s + F_e + F_f \quad (3.6)$$

where m_s is the inertia of the moving part of the actuator. $\ddot{x}_s$ is the acceleration of the piston. $P_L = P_1 - P_2$ is the differential or load pressure. d denotes the equivalent viscous damping coefficient describing the combined effects of viscous friction among the piston, and the cylinder walls, and the damping of load.

The hydraulic actuator is considered to interact with a stiffness dominant environment. Thus, the interaction force, F_e , can be expressed as:

$$F_e = k_s x_s \quad (3.7)$$

where k_s is the stiffness of the environment. Note that when the hydraulic actuator moves in free motion, the stiffness of the environment is zero, *i.e.* $k_s = 0$, and therefore $F_e = 0$. A more general form for the environment, *i.e.* mass-spring-damper, can also be considered, but the effects of the mass and damper of the load are already incorporated in m_s and d , respectively in the slave dynamic model. The dry friction acting between the piston and cylinder walls, F_f , is defined as [78]:

$$F_f = \begin{cases} 513.2 + 1219.1\dot{x}_s & \dot{x}_s > 0.0696 \\ 1015.4 - 5996.6\dot{x}_s & v_{th} \leq \dot{x}_s \leq 0.0696 \\ 985.42 & 0 \leq \dot{x}_s < v_{th}, F_u \geq 985.42 \\ F_u & 0 \leq \dot{x}_s < v_{th}, F_u < 985.42 \\ F_u & 0 > \dot{x}_s > -v_{th}, F_u > -726.97 \\ -726.97 & 0 > \dot{x}_s > -v_{th}, F_u \leq -726.97 \\ -739.7 - 2545.4\dot{x}_s & -0.0805 \leq \dot{x}_s \leq -v_{th} \\ -426.9 + 1339.4\dot{x}_s & \dot{x}_s < -0.0805 \end{cases} \quad (3.8)$$

where $F_u = A(P_1 - P_2) - F_e$. v_{th} denotes the threshold velocity, and is set to 0.005 m/s for the simulated hydraulic actuator [78].

Dynamics of the valve is described as a typical second-order system which is adequate for many industrial applications [79]:

$$\ddot{x}_v + 2\zeta_v\omega_v \dot{x}_v + \omega_v^2 x_v = k_v\omega_v^2 u \quad (3.9)$$

In (3.9), u and x_v are servovalve input voltage and the spool displacement, respectively. k_v represents the valve spool position gain. ω_v and ζ_v denote the natural frequency and damping ratio respectively, and they characterize magnitude and phase responses of the transient behavior of the servovalve. In order to model the fluid pressure behavior inside the cylindrical chambers of the hydraulic actuator, the temperature and the density of fluid are assumed to be constant, and the effect of both internal and external leakages are neglected.

The model described above is transformed into a state-space model. The following state vector ($\vec{x}$) is used for describing the dynamics of the slave actuator.

$$\vec{x} = [x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6]^T = [x_s \ \dot{x}_s \ P_1 \ P_2 \ x_v \ \dot{x}_v]^T \quad (3.10)$$

Therefore, the dynamic model of the slave actuator is represented as a state-space model as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{A}{m_s}(x_3 - x_4) - \frac{d}{m_s}x_2 - \frac{k_s}{m_s}x_1 - \frac{F_f}{m_s} \\ \dot{x}_3 = \frac{\beta_h}{Ax_1 + \bar{V}_1}(Q_1 - Ax_2) \\ \dot{x}_4 = \frac{\beta_h}{A(L - x_1) + \bar{V}_2}(-Q_2 + Ax_2) \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = -2\zeta_v\omega_v x_6 - \omega_v^2 x_5 + k_v\omega_v^2 u \end{cases} \quad (3.11)$$

Note that u is the control signal at the slave hydraulic actuator, and F_f is defined by Equation (3.8), and by replacing $\dot{x}_s$ with x_2 .

The numerical simulation of the above model is generated using the fourth-order Runge-Kutta integration method. System parameters used in the simulations are given in Table 3.1. Values of the hydraulic function parameters were obtained directly from manufacturers' data sheets or by experimental verification [80].

Table 3.1 Parameters used in simulation of the hydraulic actuator.

Parameter	Symbol	Value
Supply pressure	P_s	17.2 MPa (2500 psi)
Tank pressure	P_r	0
Combined mass of piston and rod	m_s	12.3 kg
Viscous damping coefficient	d	50 Ns/m
Actuator stroke	L	0.609 m
Piston area	A	$6.33 \times 10^{-4} \text{ m}^2$
Volume of connecting lines	$\bar{V}_1, \bar{V}_2$	$8.87 \times 10^{-5} \text{ m}^3$
Valve spool position gain	k_v	$4.06 \times 10^{-5} \text{ m/V}$
Valve natural frequency	ω_v	175 Hz
Valve damping ratio	ζ_v	0.5
Orifice coefficient of discharge	c_d	0.6
Hydraulic fluid density	ρ	847.16 kg/m ³

3.2.2. Slave hydraulic manipulator

Figure 3.3 illustrates the mobile hydraulic manipulator, a 4-DOF Kodiak manipulator which is mounted atop a 6-DOF Stewart platform. The environment consists of a frame replicating a segment of transmission line [81]. A hot stick is attached to the robot end-effector. The tested hand-controllers are a conventional seven-function joystick and a PHANTOM Desktop haptic device.

The Kodiak hydraulic manipulator DOFs are: a rotation about vertical axis (arm), three rotations about horizontal axes (shoulder, main elbow, and extended elbow), and two wrist rotations (yaw and roll). In addition, an actuator is provided at the end-effector,

which is not considered as a DOF, and used to open and close the jaw. The hydraulic manipulator and the hand-controller can be connected to the same PC using parallel port and data acquisition boards, respectively. Therefore, there is no network delay when the master and slave sites are not connected through the communication channel [82]. In this case, the control loop works at 500 Hz (sampling time of 2ms).

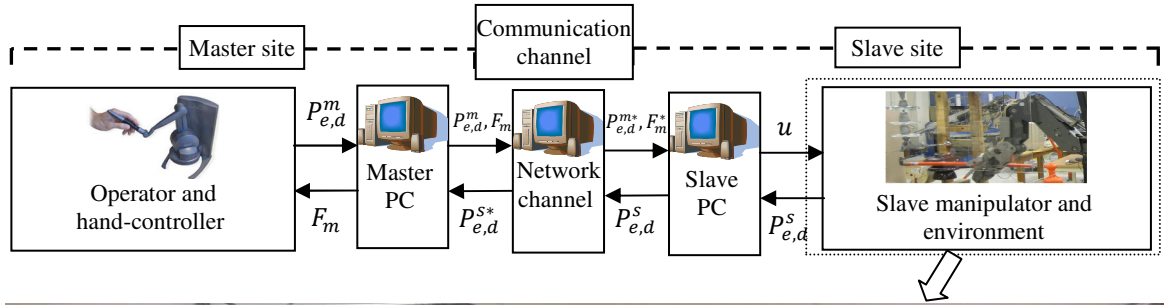


Figure 3.4 Teleoperated hydraulic manipulator setup. The superscript “*” in $P_{e,d}^{s*}$ and F_m^* denotes a delayed/lossy version of displacement and force.

The motion base is composed of six single-rod hydraulic actuators; each is controlled by a proportional valve. In the middle of each actuator, a linear displacement sensor is installed that measures the displacements. These hydraulic actuators are installed in pairs to the mechanism base, crossing over to three points on a top plate. The hydraulic manipulator is placed on a corner of the top plate. There exist three linear movements (lateral, longitudinal and vertical), and three rotations (pitch, roll and yaw). A computer controls the Stewart platform using a QuaRC interfacing board. This experimental setup is used to perform different transmission line maintenance tasks (see Section 2.1) using two hand-controllers: a conventional joy stick and a PHANTOM Desktop haptic device.

A schematic of the slave hydraulic manipulator and corresponding coordinate frames are illustrated in Figure 3.5. In designed experiments, the actuators creating the yaw and roll rotations were switched off, and only the first four DOFs were employed to run the manipulator. The hotstick is attached to the last link and is always kept horizontal. In Figure 3.5, $\{x_e^s y_e^s z_e^s\}$ denotes the coordinate system attached to the manipulator end-effector, and the fixed (global) coordinate system is denoted by $\{x_0^s y_0^s z_0^s\}$. The superscript ‘s’ indicates the parameter belongs to the slave (hydraulic manipulator). In order to always keep the hot-stick parallel to the horizontal plane, the joint angle θ_4^s (extended elbow) is expressed in terms of θ_2^s and θ_3^s , as follows:

$$\theta_4^s = -\theta_3^s - \theta_2^s \quad (3.12)$$

Thus, only the first three angular displacements of the manipulator ($\theta_{i=1,2,3}^s$) are required to solve the kinematics.

Let $\vec{P}_{e,d}^s = [x_e^s \ y_e^s \ z_e^s]^T$ denote the desired coordinate of hydraulic manipulator end-effector. By solving the inverse kinematics of the manipulator, the desired angular displacements ($\theta_{i=1..4}^s$) are calculated using [83]:

$$\theta_1^s = \tan^{-1} \left(\frac{y_e^s}{x_e^s} \right) \quad (3.13)$$

$$\theta_2^s = \tan^{-1} \left(\frac{k_2}{k_1} \right) + \tan^{-1} \left(\frac{\pm \sqrt{k_1^2 + k_2^2 - k_3^2}}{k_3} \right) \quad (3.14)$$

$$\theta_3^s = \tan^{-1} \left(\frac{2l_2k_2c_2 - 2l_2k_1s_2}{k_1^2 + k_2^2 - l_2^2 - l_3^2} \right) \quad (3.15)$$

Using Equation (3.12), we have:

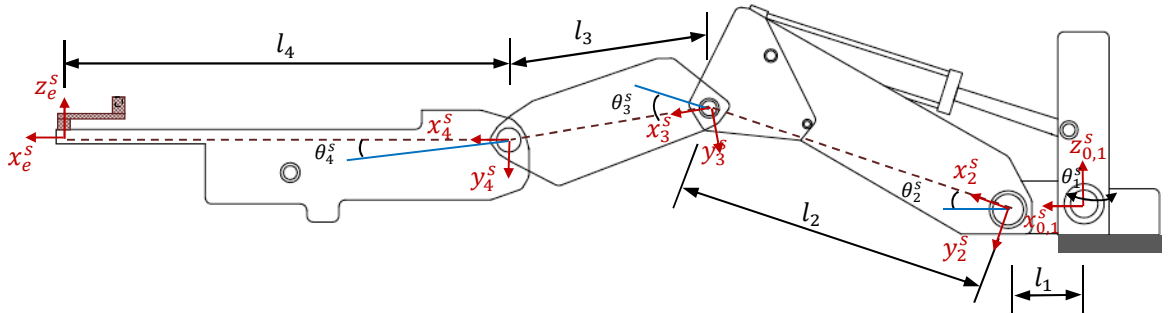
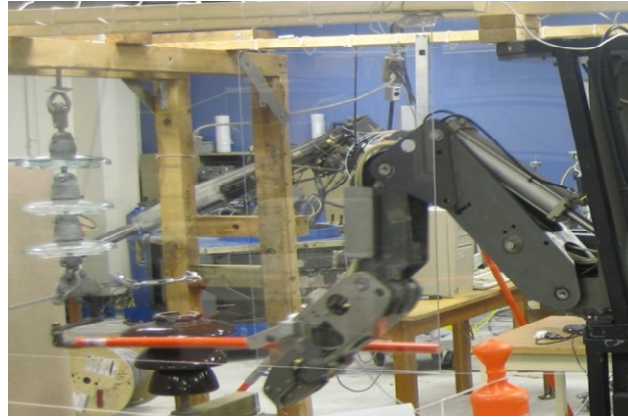


Figure 3.5 Coordinate frames of slave hydraulic manipulator. DOFs are: vertical rotation (θ_1^s), shoulder (θ_2^s), main elbow (θ_3^s), and extended elbow (θ_4^s) [4].

$$\theta_4^s = -\tan^{-1}\left(\frac{k_2}{k_1}\right) - \tan^{-1}\left(\frac{\pm\sqrt{k_1^2 + k_2^2 - k_3^2}}{k_3}\right) - \tan^{-1}\left(\frac{2l_2k_2c_2 - 2l_2k_1s_2}{k_1^2 + k_2^2 - l_2^2 - l_3^2}\right) \quad (3.16)$$

where $c_i = \cos(\theta_i^s)$, $s_i = \sin(\theta_i^s)$, and

$$k_1 = x_e^s c_1 + y_{e,d}^s s_1 - l_1 - l_4 \quad (3.17)$$

$$k_2 = -z_e^s \quad (3.18)$$

$$k_3 = \frac{k_1^2 + k_2^2 + l_2^2 - l_3^2}{2l_2} \quad (3.19)$$

A schematic of the Stewart platform is shown in

Figure 3.6. As observed, there are six hydraulic actuators that are commanded to generate the desired posture (position and orientation) of frame $\{X^t Y^t Z^t\}$. The position, D , and orientation, R , of frame $\{X^t Y^t Z^t\}$ with respect to frame $\{X^b Y^b Z^b\}$ are defined as follows:

$$D = [D_x \ D_y \ D_z]^T \quad (3.20)$$

$$R = \begin{bmatrix} \alpha_x & \beta_x & \gamma_x \\ \alpha_y & \beta_y & \gamma_y \\ \alpha_z & \beta_z & \gamma_z \end{bmatrix} \quad (3.21)$$

With reference to

Figure 3.6, and as shown in [84], the length of each actuator, $L_{i=1\dots6}$, is given by:

$$L_i = |S_i| = \sqrt{S_{i,x}^2 + S_{i,y}^2 + S_{i,z}^2} \quad (3.22)$$

where

$$S_i = [S_{i,x} \ S_{i,y} \ S_{i,z}]^T = D + RT_i - B_i \quad (3.23)$$

In (3.23), D and R are given by Equation (3.20). B_i and T_i are position vectors of the endpoints of each actuator with respect to frames $\{X^b Y^b Z^b\}$ and $\{X^t Y^t Z^t\}$, respectively.

They are defined as below:

$$\begin{cases} T_1 = \begin{bmatrix} L_t - r_t & \frac{-a}{2} & -H_t \end{bmatrix}^T \\ T_2 = \begin{bmatrix} L_t - r_t & \frac{a}{2} & -H_t \end{bmatrix}^T \\ T_3 = \begin{bmatrix} \frac{a}{2} \sin 60^\circ - (L_t - r_t) \sin 30^\circ & (L_t - r_t) \cos 30^\circ + \frac{a}{2} \sin 30^\circ & -H_t \end{bmatrix}^T \\ T_4 = \begin{bmatrix} -r_t & (L_t - r_t) \cos 30^\circ - \frac{a}{2} \sin 30^\circ & -H_t \end{bmatrix}^T \\ T_5 = \begin{bmatrix} -r_t & -(L_t - r_t) \cos 30^\circ + \frac{a}{2} \sin 30^\circ & -H_t \end{bmatrix}^T \\ T_6 = \begin{bmatrix} \frac{a}{2} \sin 60^\circ - (L_t - r_t) \sin 30^\circ & -(L_t - r_t) \cos 30^\circ - \frac{a}{2} \sin 30^\circ & -H_t \end{bmatrix}^T \end{cases} \quad (3.24)$$

and,

$$\begin{cases} B_1 = \begin{bmatrix} r_b & -(L_b - r_b) \cos 30^\circ + \frac{c}{2} \sin 30^\circ & H_b \end{bmatrix}^T \\ B_2 = \begin{bmatrix} r_b & (L_b - r_b) \cos 30^\circ - \frac{c}{2} \sin 30^\circ & H_b \end{bmatrix}^T \\ B_3 = \begin{bmatrix} (L_b - r_b) \sin 30^\circ - \frac{c}{2} \sin 60^\circ & (L_b - r_b) \cos 30^\circ + \frac{c}{2} \sin 30^\circ & H_b \end{bmatrix}^T \\ B_4 = \begin{bmatrix} -(L_b - r_b) & \frac{c}{2} & H_b \end{bmatrix}^T \\ B_5 = \begin{bmatrix} -(L_b - r_b) & -\frac{c}{2} & H_b \end{bmatrix}^T \\ B_6 = \begin{bmatrix} (L_b - r_b) \sin 30^\circ - \frac{c}{2} \sin 60^\circ & -(L_b - r_b) \cos 30^\circ - \frac{c}{2} \sin 30^\circ & H_b \end{bmatrix}^T \end{cases} \quad (3.25)$$

where L_t , L_b , r_t and r_b are calculated using:

$$L_t = (a + b) \sin 60^\circ, \quad L_b = (c + d) \sin 60^\circ \quad (3.26)$$

$$r_t = \frac{\sqrt{3}}{6} (2a + b), \quad r_b = \frac{\sqrt{3}}{6} (2c + d) \quad (3.27)$$

The characteristics of the Kodiak manipulator and the Stewart platform are listed in Table 3.2.

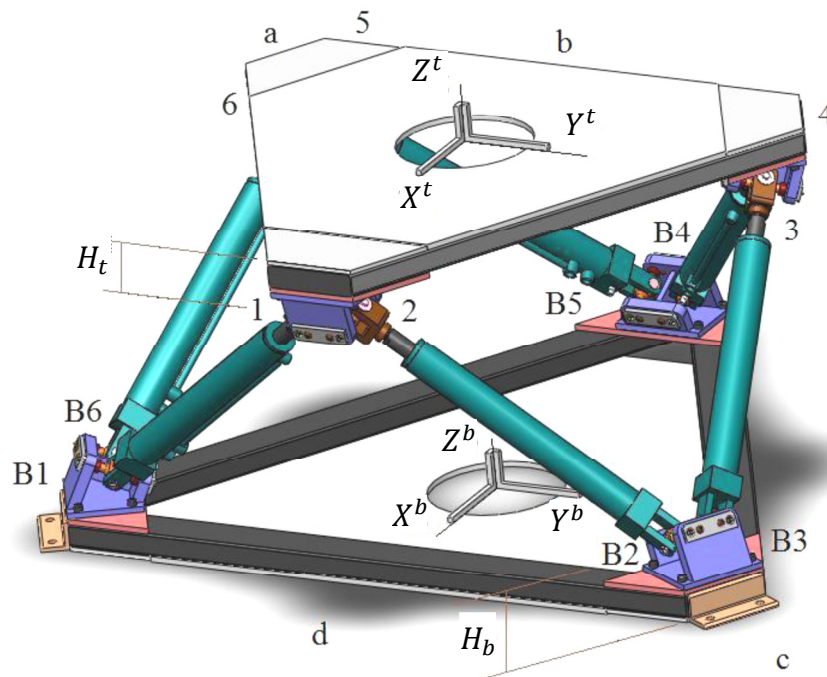


Figure 3.6 Coordinate systems of Stewart platform.

Table 3.2 Specifications of Kodiak 1000 hydraulic manipulator and Stewart platform.

	Parameter	Length (mm)
Kodiak manipulator	Extension link, l_1	133
	Shoulder, l_2	459
	Elbow, l_3	342
	Extended elbow, l_4	1354
	Top plate, short side, a	101.6
	Top plate, long side, b	1045.5
Stewart platform	Bottom plate, short side, c	101.6
	Bottom plate, long side, d	1368.0
	Joint distance from bottom plate, H_b	140.5
	Joint distance from top plate, H_t	145.8

Figure 3.7 illustrates the schematic of a typical link, which is driven by a single-rod hydraulic actuator. P_s and P_r are the hydraulic pump (supply) and tank pressures (return), respectively. u_i denotes the control signal applied to the hydraulic valve [75]. $\theta_{i,a}^s$ is the actual value of the joint angular displacement and is measured by the Hall effect sensor. The desired value of joint displacement, $\theta_{i,d}^s$, is calculated using Equations (3.12) to (3.15). The difference between the actual and desired joint displacements (e_i^s) is continuously calculated, and sent to the controller in order to generate the appropriate control signal reducing the position error.

The controller must (i) have excellent tracking and regulating abilities, (ii) respond quickly to variations of the set point, (iii) reverse the directions quickly without overshoot, and (iv) retain above properties for both large and small changes in the set point. The implementation is made possible by using the nonlinear PI (NPI) controller for each joint of the manipulator [85]. The NPI controller was shown to improve tracking accuracy by a factor of five, as compared to the conventional PI controller with fixed

gains, without sacrificing regulation accuracy or robustness [85]. The accuracy of the NPI controller is about 0.2 degrees [85].

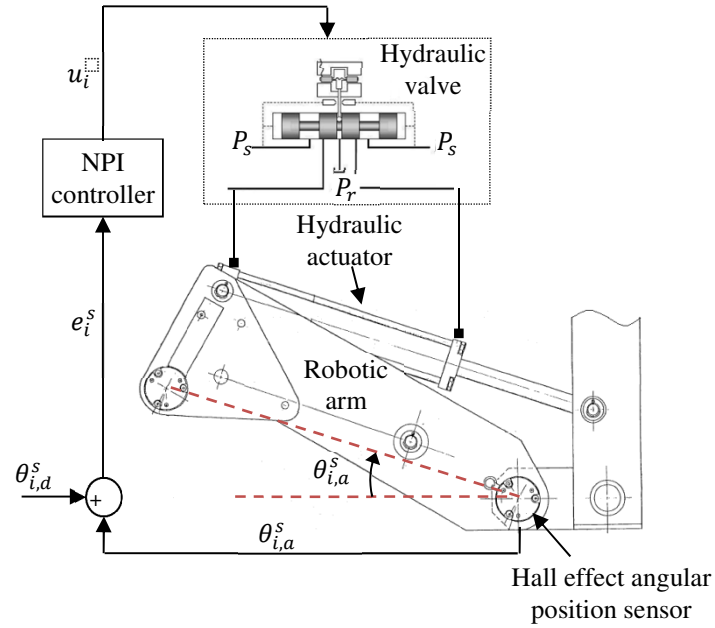


Figure 3.7 Schematic of a manipulator link driven by a single-rod hydraulic actuator.

3.3. Hand-Controllers

Two mapping modes are used: joint mapping (JM) and end-effector mapping (EM). In JM mode, angular displacements of the first 3 DOFs of a seven-function joystick joints are mapped into displacements of hydraulic manipulator joints. Figure 3.8 depicts the coordinate system of the conventional seven-function joystick. The joystick, which is specially designed to control the Kodiak hydraulic manipulator, has the same structural geometry as the Kodiak arm. Therefore, by mapping the joints displacements, the same trajectories are anticipated at both the joystick implement and the manipulator end-effectors. In JM mode, the operator holds the joystick handle and looks at the tools located at the manipulator end-effector, to visually follow the task. By moving the

joystick, the actual angular displacement vector of joystick joint ($\vec{\theta}_a^m$) is measured by encoders, and sent to the manipulator side as desired angular displacement vector at the slave site ($\vec{\theta}_d^s$). Note that θ_4^s is calculated using Equation (3.12). Therefore, when the joystick guides the hydraulic manipulator, all four angular displacements in slave site are determinable, and the kinematics is solvable. The hydraulic actuators are then driven to achieve the required manipulator joint displacements. Therefore, the manipulator end-effector travels along the path described by the operator.

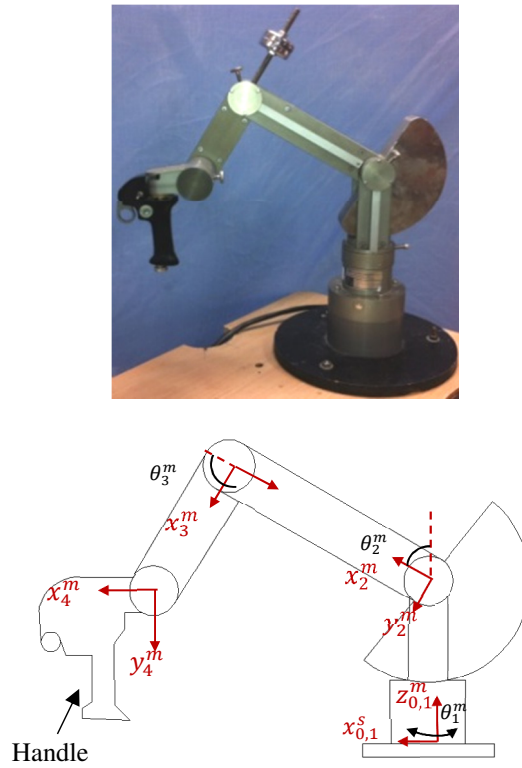


Figure 3.8 Coordinate frames of conventional seven-function joystick [4].

Figure 3.9 depicts coordinate frames of a PHANTOM Desktop/Omni haptic device which is used as the master device in the EM mode. In this mapping, the position of haptic device end-effector is mapped into the end-effector position of manipulator

$\{x_e^s y_e^s z_e^s\}$ by multiplying by the mapping factor, α_s . Indeed, by using this mapping, the desired trajectory of manipulator end-effector is formed by the actual trajectory of operator's hand at the master site (haptic device).

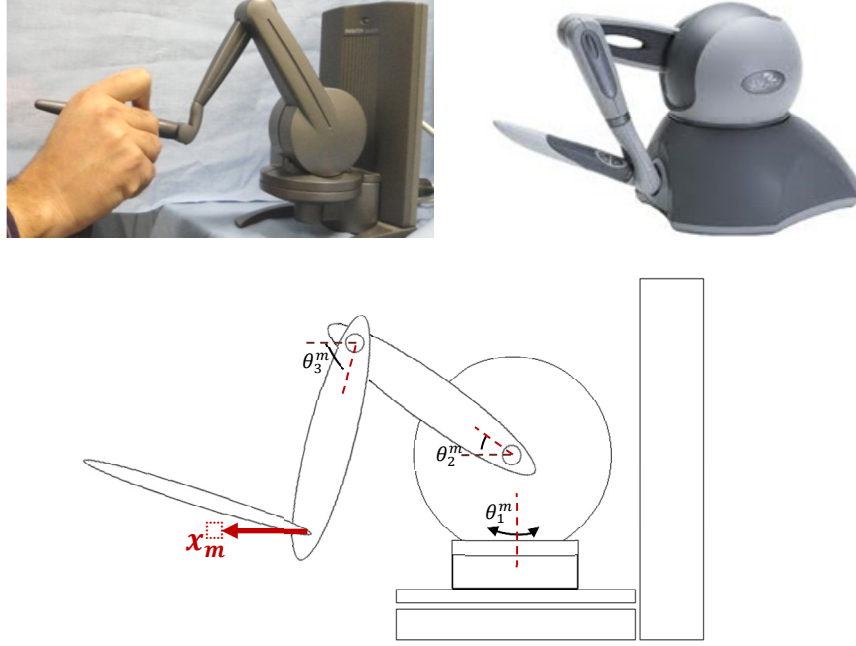


Figure 3.9 Coordinate frames of PHANToM Desktop/Omni haptic device [4].

The following equation simply describes the dynamics of the haptic device at the master site, in a single direction [86]:

$$m_m \ddot{x}_m + k_d \dot{x}_m + k_h x_m = F_h + F_m + F_b \quad (3.28)$$

where x_m represents the position of the master (see Figure 3.9). F_h is the force applied by the operator's hand and F_m denotes the master force generated by the haptic in the x_m direction. m_m and k_d represent inertia and damping coefficients of the combined operator's arm and haptic device, respectively. k_h is the stiffness of the human arm. F_b represents the backdrive friction force, and is, for example, less than 0.26 N for the PHANToM Omni device [87].

3.4. Network Emulators

3.4.1. General architecture

The communication setup, connecting master and slave sites, is shown in Figure 3.10. Data packets are transmitted from the master site to the slave site and *vice-versa* through network switches. In order to introduce an artificial time delay or packet loss into the loop, an intermediate computer, supplied with Wide Area Network emulator (WANem) or Network Simulator version 2 (NS2), is connected to the network switch. The data packets transmission is re-routed through WANem or NS2 before forwarding to the destination node.

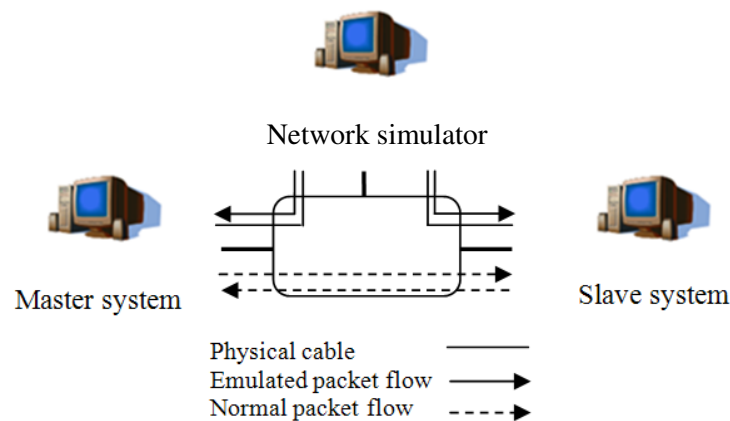


Figure 3.10 Network communication setup.

In terms of transport protocol, User Datagram Protocol (UDP) was preferred over Transmission Control Protocol (TCP) for teleoperation or real-time applications due to its shorter transmission time. The utilization of UDP as the data transmission protocol also implies that each data packet can continually be sent from one node to the other without retransmission of lost packets or acknowledgement of packets arrival. This contributes to smaller round trip time delay in the UDP-based connection.

3.4.2. Wide Area Network emulator (WANem)

WANem is an open source distribution software developed by TATA Consultancy Services (TCS) for emulating realistic network behavior in development or test environment [88]. WANem simulates various network characteristics such as network delay, packet loss, packet corruption and disconnections. The architecture of WANem is divided into three layers (see Figure 3.11). WANem is basically built upon the Linux kernel which consists of an open source Network Emulator module (NetEm), Hierarchical Token Bucket (HTB) queuing discipline for bandwidth limiting functionality, Network Packet Filtering module (NetFilter) and Connection Tracking module (ConnTrack) for TCP/IP. These modules work together to introduce artificial delay, packet loss and other scenarios in test environment [89].

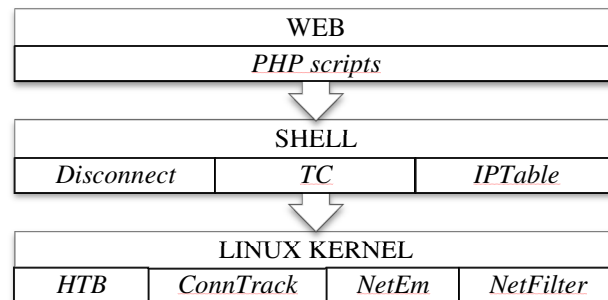


Figure 3.11 WANem architecture.

The middle layer of WANem architecture consists of a command line tool (TC), Disconnect and IPTables modules. The command line tool is used to invoke functionalities such as NetEm and HTB in the Linux kernel layer. The IPTable is used to configure the operating system (Knoppix Linux) which allows applications and users to connect through the network and stop unwanted applications and users from

communicating and interrupting the operating system. Disconnect, on the other hand, is a script to implement emulation of the network disconnection characteristics. It uses ConnTrack in the Linux kernel layer and IPTables to implement its functionality. The uppermost layer (Web) is the configuration interface for WANem, developed in PHP scripts. Some examples of WANem used in the research works can be found in [90, 91, 92, 93].

In order to verify the performance of WANem, several tests could be conducted before starting each set of experiments. The performance of WANem was tested using “ping” command where the time delays at WANem are set to be 0 ms, 100 ms, 200 ms and 500 ms in both forward (master to slave) and backward (slave to master) directions independently. The tests resulted in average round trip delays of 0 ms, 204 ms, 403 ms and 1005 ms, respectively. Therefore, the accuracy of WANem in creating artificial time delay in the communication channel is reasonable.

3.4.3. Network simulator version 2 (NS2)

Network Simulator version 2 (NS2) is a packet-level simulation tool, and is used to study the behavior of networks. The NS2 provides functions to generate simulation scenarios, and protocols for both wired and wireless networks [94]. The NS2 was chosen for its availability, widespread use, and ability to be developed [95]. In the setup, used in this research, the NS2 is built upon two programming languages. Most of the core functions of NS2 are built using C++. The C++ classes provide an interface that is exposed through the Object-oriented Tool Command Language (OTcl). OTcl scripts are mainly used to specify parameters and details for simulation scenarios generation. Users

have access to the source code and are able to write extensions to NS2 in either OTcl or C++.

Figure 3.12 shows the software components of the network emulator. When NS2 is run under the network emulation mode, it uses different objects to represent the application layer traffic generators and the transport layer agents. In the emulation mode, NS2 captures incoming packets, and then injects them into the simulation. These packets are then delayed or dropped based on the results of the ongoing simulation. After the packets, injected into the simulation, are appropriately delayed, they are forwarded towards the intended destination by the network emulator. Firstly, NS2 uses the Berkely Packet Filter kernel agent to capture data-link layer frames [96]. The captured data is injected into the simulation by the attached Tap Agents, which introduce simulation packets containing live data as their payload. Once the packets (with live data) are introduced, they travel through the network and link layers implemented by the NS2 as normal. Afterwards, the network emulator must attempt to forward packets according to the calculated delay. To accomplish this, the NS2 uses a real-time scheduler which waits for the scheduled time before dispatching events in the simulation [97]. However, due to timing errors and computational load in emulator computer, the actual delay produced by the network emulator may be greater than the calculated delay. The error in the delay time, produced by the network emulator, is called the slop factor [98]. In order to test the accuracy of the NS2 scheduler during the experiment, ping packets were sent between the master computer and the network emulator. The emulator was set to reply to the ping probes with a specified constant delay. The real accuracy of the real-time scheduler, in fact, depends on the computational load of the computer. Since the extra delays,

generated erroneously by the network emulator, are small as compared to the processing delay of the master and slave programs, the accuracy of the NS2 scheduler is satisfactory for the proposed experiments.

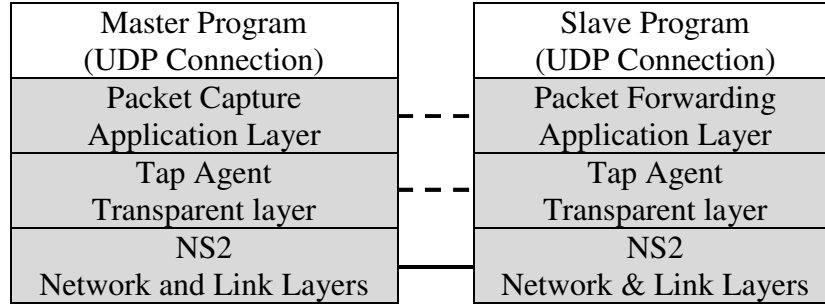


Figure 3.12 Protocol stack of NS2 in emulation mode. Shaded boxes indicate components that are part of NS2. Solid and dashed lines indicate physical and logical connections, respectively.

3.5. Summary

This chapter introduced specifications of the experimental test rigs, employed in this thesis, followed by describing required formulations. Each test rig consisted of a master site (an operator, a master PC and a hand-controller), a slave site (a hydraulic system and a slave PC), and a network emulator (WANem or NS2). Master devices were a conventional joystick, a PHANToM Omni haptic device, and a PHANToM Omni haptic device. Slave hydraulic systems included a double-rod valve-controlled hydraulic actuator (single-DOF) and a Kodiak hydraulic manipulator installed on a Stewart platform (multi-DOF).

CHAPTER 4

WIRELESS CONTROL OF HYDRAULIC ACTUATORS

4.1. Introduction

In this chapter, effects of communication channel on the performance of a hydraulic actuator are examined that help to choose network parameters by which the teleoperated system operates without significant impacts on its performance. The goal is to show how transparently and stably hydraulic actuators work under different conditions of delayed and lossy communication channels. The study is first performed on the hydraulic actuator comprising haptic device (Figure 3.9), a valve-controlled hydraulic actuator (see Section 3.2.1) and communication channel emulated by WANem (described in Section 3.4.2). Two sets of experiments are conducted when the hydraulic actuator works under a dedicated communication channel and a wireless channel. In first set of experiments, the hydraulic actuator is controlled by four control schemes: force reflection (FR), position error (PE), combined force reflection and position error (FP), and four channels (FC). Performances of four control schemes are then compared using three criteria: position tracking, force tracking, and fidelity of the perceived stiffness. The best control scheme is

then employed to investigate the performance of the teleoperated system under a wireless channel.

The second set of experiments studies how to select network parameters when the hydraulic actuator is controlled through a wireless communication channel. In this set, the wireless communication channel is emulated using the NS2 simulator (see Section 3.4.3). Extensive experiments are conducted, and effects of time-varying delays and losses on performance of the system are re-evaluated. Next, a set of performance charts is constructed. These network parameters are: configuration of environment obstruction, antenna transmission power, and distance between the master and slave sites.

4.2. Performance Evaluation under Dedicated Channels

4.2.1. Test procedure

This section investigates how constant time delays and packet losses affect performance of a teleoperated hydraulic actuator utilizing different control schemes. The schemes run in the master PC to control the haptic device. The slave PC simulates the dynamics of a valve-controlled hydraulic actuator and the linear spring environment (see Figure 3.2). The two PC's are connected through a computer running the WANem software. Even though the employed hydraulic actuator is only a simulated model, the accuracy of the model as compared to the real actuator has been verified earlier [80].

In all experiments, the operator manipulated the master haptic device using a particular control scheme through an emulated communication channel to follow a fixed trajectory close to the path depicted in Figure 4.1. This path includes both free and constrained motions. In constrained motion, the slave manipulator was virtually

interacting with the environment emulated by a linear spring having a stiffness of 45 kN/m . The same operator performed all experiments. The operator was asked to hold the stylus of the haptic device like holding a pen and trace the given path as closely as possible (see Figure 4.1).

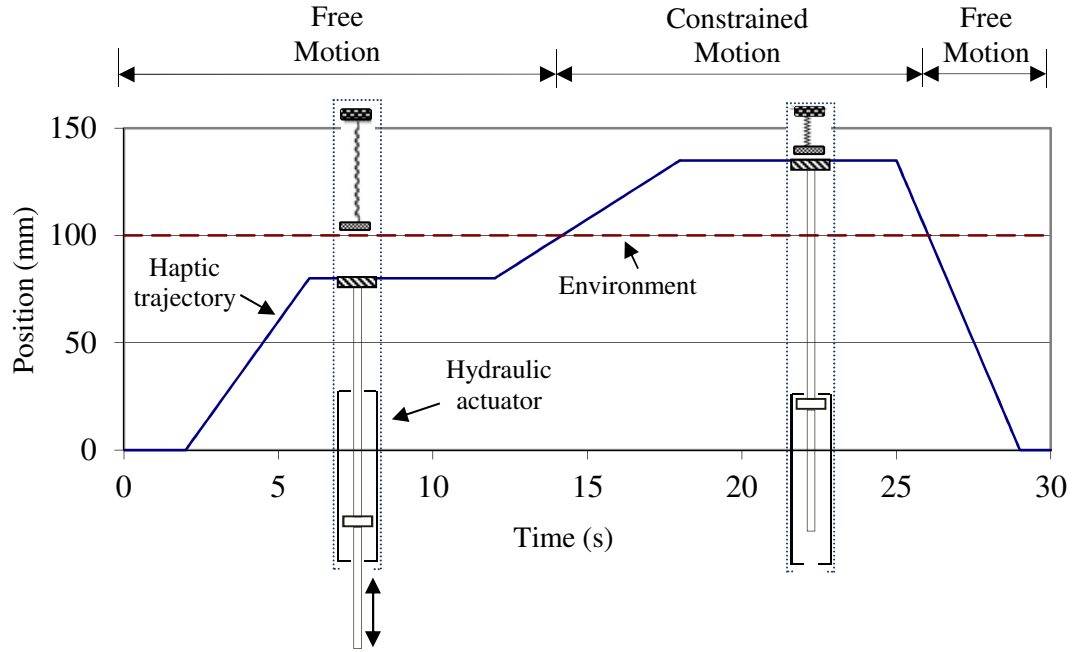


Figure 4.1 Typical trajectory for haptic device showing master displacement, x_m .

The operator repeats the same task for all control schemes and having different configurations of communication channel as shown in Table 4.1. In total, 48 experiments were conducted involving all four control schemes, each with three constant time delays (100 ms, 500 ms and 1000 ms) and four different packet losses (0%, 25%, 50% and 75%). Table 4.1 shows the scenarios. Although the operator was asked to repeat the same free and constrained motions in each experiment, some deviations from trajectories were unavoidable. Due to the similarity of results, only results of UD00, UD02 and UD30 are

presented in details. The results are analyzed using (i) the Root Mean Square (RMS) index (quantitative study), and (ii) observing the signal tracking (qualitative study) [99, 100].

Table 4.1 Network variables used in experiments: one-way delay (TD) and packet loss rate (PL).

	UD00	UD01	UD02	UD10	UD11	UD12	UD20	UD21	UD22	UD30	UD31	UD32
TD (ms)	100	500	1000	100	500	1000	100	500	1000	100	500	1000
PL (%)	0	0	0	25	25	25	50	50	50	75	75	75

4.2.2. Control schemes

Four control schemes namely, force reflection (FR), position error (PE), hybrid which is combination of force reflection and position error (FP) and four channels (FC) architecture were selected in this study; since they were good in terms of their performance as concluded in [13]. In order to compare these control schemes, the controller gains were tuned for similar performance under free motion using the communication channel configured at 0 ms time delay and 0% packet loss. There were then kept constant for the entire test.

- *Force reflection* (FR): In the FR control scheme, the force generated at the master site, F_m^{FR} , is proportional to the interaction force with the environment transmitted from the slave to master site, $F_{e,d}$. The control signal at the slave site, u^{FR} , on the other hand is proportional to the position error between master (haptic device, $x_{m,d}$) and slave (hydraulic actuator, x_s) [58].

$$\begin{aligned}
 F_m^{FR} &= H_c^{FR} F_{e,d} \\
 u^{FR} &= K_c^{FR} (x_{m,d} - x_s)
 \end{aligned}
 \tag{4.1}$$

where H_c^{FR} and K_c^{FR} are the control gains. The subscript "d" in $x_{s,d}$ and $F_{e,d}$ denotes a delayed variable due to communication delay in the teleoperated system.

- *Position error (PE)*: In the PE control architecture, the force generated at the master site, F_m^{PE} , is proportional to the position error between master and slave. As a result, the operator has some haptic sensations of the environment helping her/him to control the position of the slave hydraulic actuator from the master site. The control signal generated at the slave site, u^{PE} , is also proportional to the position error between master and slave [58].

$$\begin{aligned} F_m^{PE} &= G_c^{PE} (x_m - x_{s,d}) \\ u^{PE} &= K_c^{PE} (x_{m,d} - x_s) \end{aligned} \quad (4.2)$$

where G_c^{PE} and K_c^{PE} are control gains.

- *Hybrid, combined force reflection and position error (FP)*: In the FP control scheme, the force generated at the master site, F_m^{FP} , is expressed as a function of both the position error between master and slave as well as the interaction force, $F_{e,d}$ with the environment. This controller has both characteristics of FR and PE control schemes. As for the control signal at the slave site, u^{FP} , it is still the same as the previous control architectures which is proportional to the position error between the master (haptic device) and the slave (hydraulic actuator).

$$\begin{aligned} F_m^{FP} &= H_c^{FP} F_{e,d} + G_c^{FP} (x_m - x_{s,d}) \\ u^{FP} &= K_c^{FP} (x_{m,d} - x_s) \end{aligned} \quad (4.3)$$

In Equation (4.3), H_c^{FP} , G_c^{FP} and K_c^{FP} are the control gains.

- *Four channels (FC)*: The four channels control architecture has four communication channels for information exchange between master and slave sites. The force generated at

the master site, F_m^{FC} , and the control signal, u^{FC} , are expressed as functions of both velocity and force information exchanged between the master and slave sites as follows [5]:

$$\begin{aligned} F_m^{FC} &= -C_6 F_h + C_m \dot{x}_m + \hat{F}_{e,d} + \hat{v}_{s,d} \\ u^{FC} &= C_5 F_e - C_s \dot{x}_s + \hat{F}_{m,d} + \hat{v}_{m,d} \end{aligned} \quad (4.4)$$

where

$$\hat{v}_{m,d} = C_1 \dot{x}_{m,d} ; \hat{F}_{m,d} = C_3 F_{m,d} ; \hat{v}_{s,d} = C_4 \dot{x}_{s,d} ; \hat{F}_{e,d} = C_2 F_{e,d} \quad (4.5)$$

Note that C_5 and C_6 are the feedforward gains and C_m and C_s denote the feedback gains. Besides, C_1, C_2, C_3 and C_4 are dynamic parameters. In order to experimentally achieve perfect transparency, the following conditions must be met:

$$C_1 = Z_{cs} ; C_4 = -Z_{cm} ; C_5 = (C_3 - 1) ; C_6 = (C_2 - 1) \quad (4.6)$$

In (4.6), $Z_{cs} = Z_s + C_s$ and $Z_{cm} = Z_m + C_m$, where Z_m and Z_s are the master and slave impedances, respectively.

Since, the main objective of this study is to investigate the effects of time delay and packet loss on the system performance, the implemented time delayed versions of x_s and F_e , transmitted to the master site via a communication channel, are modeled in Laplace domain (s domain) by the following equations:

$$\begin{aligned} x_{s,d}(s) &= e^{-sT_f} x_s(s) \\ F_{e,d}(s) &= e^{-sT_f} F_e(s) \end{aligned} \quad (4.7)$$

where T_f is the forward time delay (from slave to master), $x_{s,d}$ represents the actuator position and $F_{e,d}$ refers to the forces externally applied to the delayed system.

The parameters x_m and F_m , which are transmitted to the slave site through a communication channel, are also expressed in Laplace domain as follows:

$$\begin{aligned}
x_{m,d}(s) &= e^{-sT_b}x_m(s) \\
F_{m,d}(s) &= e^{-sT_b}F_m(s)
\end{aligned}
\tag{4.8}$$

where T_b is the backward (from master to slave) communication time delay.

In this study, time delays are assumed to be the same in both backward and forward directions. Thus, Equations (4.7) and (4.8) can be expressed with common term of time delay (TD), where $TD = T_f = T_b$.

4.2.3. Experimental results using simulation of hydraulic actuator

In the experiments, the stability of the entire teleoperated control system was investigated by visually observing if the oscillations in the responses are bounded [57]. Once stability was ensured, the performance of the system was examined. Performance refers to how accurate the slave system follows the command of the master system as well as how transparent the environment is to the operator.

4.2.3.1 Position tracking

Figure 4.2 illustrates the position tracking results of all four control schemes during free and constrained motions. In general, as shown in Figure 4.2, the position tracking of all four control schemes is fairly good even with the changes in the percentage of packet loss. However, it is observed that the slave system under FC control scheme showed more fluctuations during the tracking of haptic device movement as compared to FR, PE and FP schemes.

By comparing results of UD00 and UD02 in Figure 4.2, it is observed that with the increase of time delay at a given packet loss, the position error also increases. With

reference to results of UD30, there are periods where the actuator does not appear to respond to the input changes. This is believed to be due to the effect of the high rate of packet loss (75%), during which no new information is transmitted to the slave site. Therefore, the slave does not see any changes in the input, and does not move. The comparison study of position tracking, $(x_m - x_s)$, for three time delays including 100 ms, 500 ms and 1000 ms with PL=0% is summarized in Figure 4.2. It is obvious that the position error increases with increasing time delay. By comparing the responses with time delays 100 ms and 1000 ms in Figure 4.2, it is observed that FC has the largest position error amongst all four control schemes. Moreover, Figure 4.2 indicates that the FC controller has more oscillations in response, as compared to other schemes. As observed in Figure 4.3, the position errors of all schemes become smaller with the decrease of time delay.

As illustrated in Figure 4.4, by comparing the RMS values of position errors given a similar packet loss (UD00, UD01 and UD02), it is seen that the longer the time delay, the larger the RMS value is. On the contrary, by comparing cases of similar time delays but variable packet losses (*e.g.* UD00, UD10, UD20 and UD30), we cannot draw a general conclusion on the effect of packet losses on position errors. According to the experimental results, FP exhibited the best of position tracking behavior among the tested control schemes for long time delays.

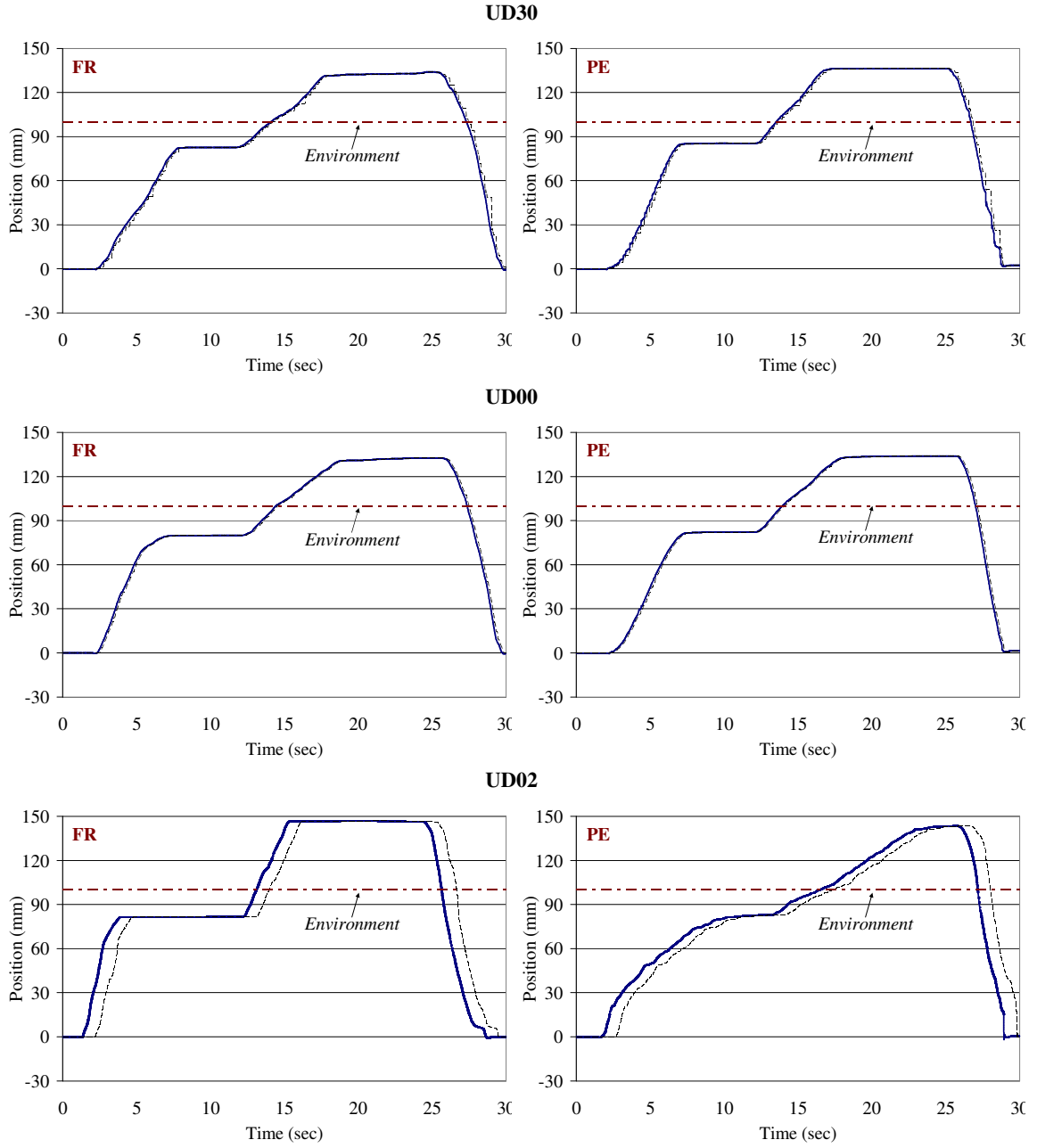


Figure 4.2 Displacements, x_m and x_s ; solid line: haptic device (master); dashed line: hydraulic actuator (slave). Responses are shown for TD=100 ms and PL=75% (UD30), for TD=100 ms and PL=0% (UD00), and for TD=1000 ms and PL=0% (UD02).

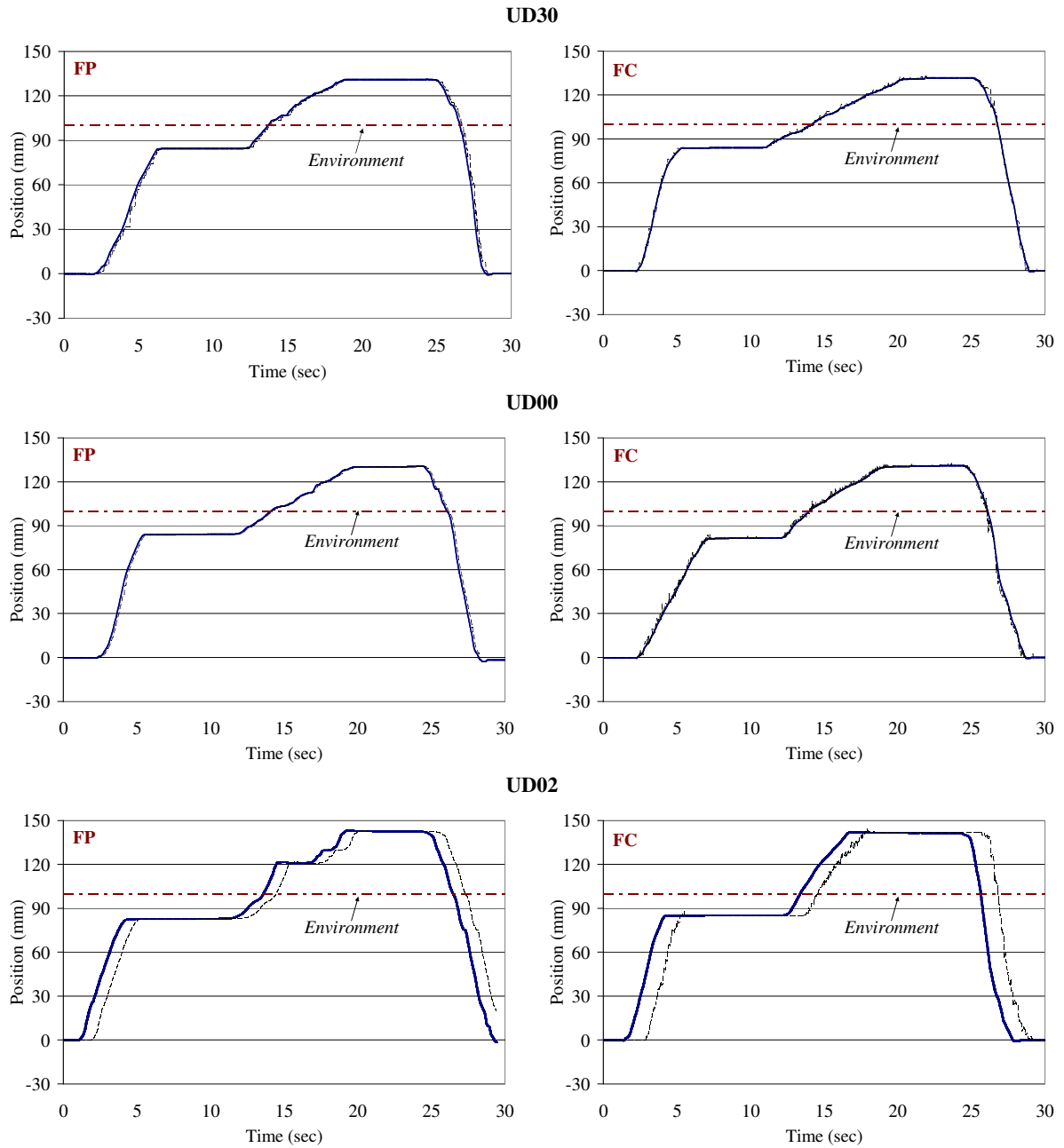


Figure 4.2 (contd.) Displacements, x_m and x_s ; solid line: haptic device (master); dashed line: hydraulic actuator (slave). Responses are shown for TD=100 ms and PL=75% (UD30), for TD=100 ms and PL=0% (UD00), and for TD=1000 ms and PL=0% (UD02).

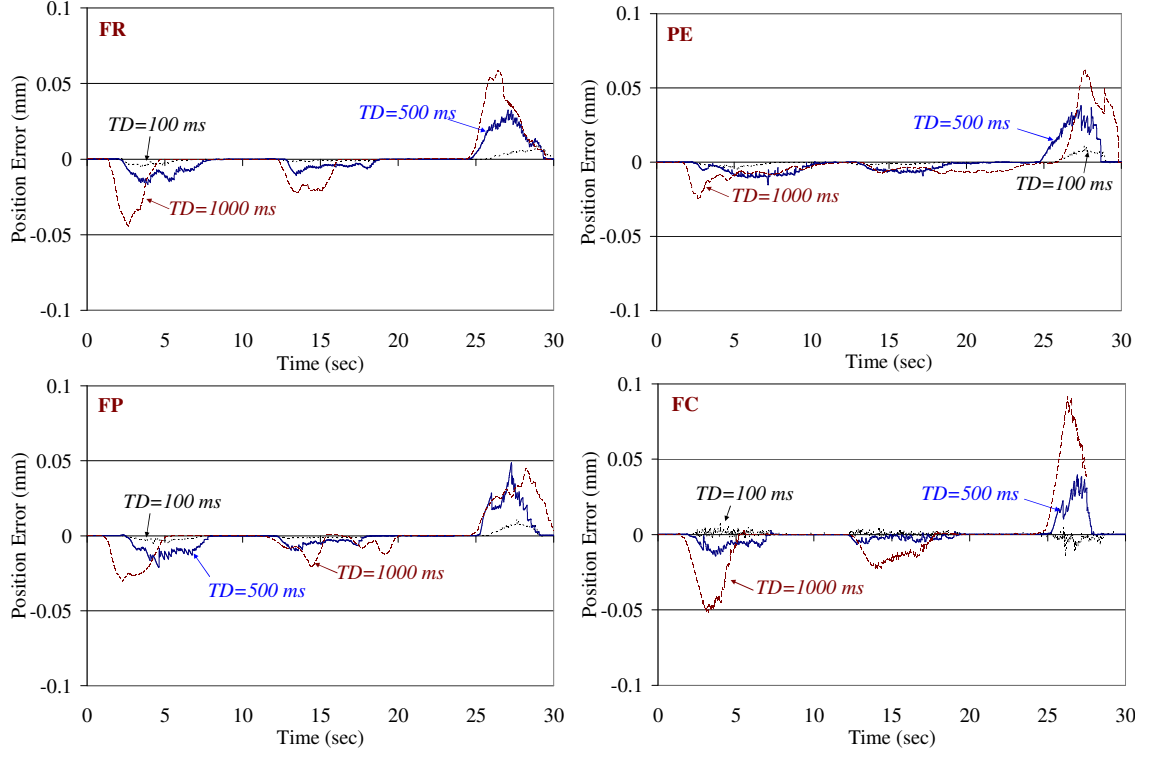


Figure 4.3 Displacement errors, $(x_m - x_s)$, when PL=0%. Dotted line: TD=100 ms (UD00); solid line: TD=500 ms (UD01); dashed line: TD=1000 ms (UD02).

The RMS values of position errors for all 48 experiments including the combination of three time delays (100 ms, 500 ms and 1000 ms) and four different packet losses (0%, 25%, 50% and 75%) are depicted in Figure 4.4. The variations of position error with respect to different time delays and packet losses can clearly be observed in this figure. As shown in Figure 4.4, an increase in time delay results in increased position error for all control schemes

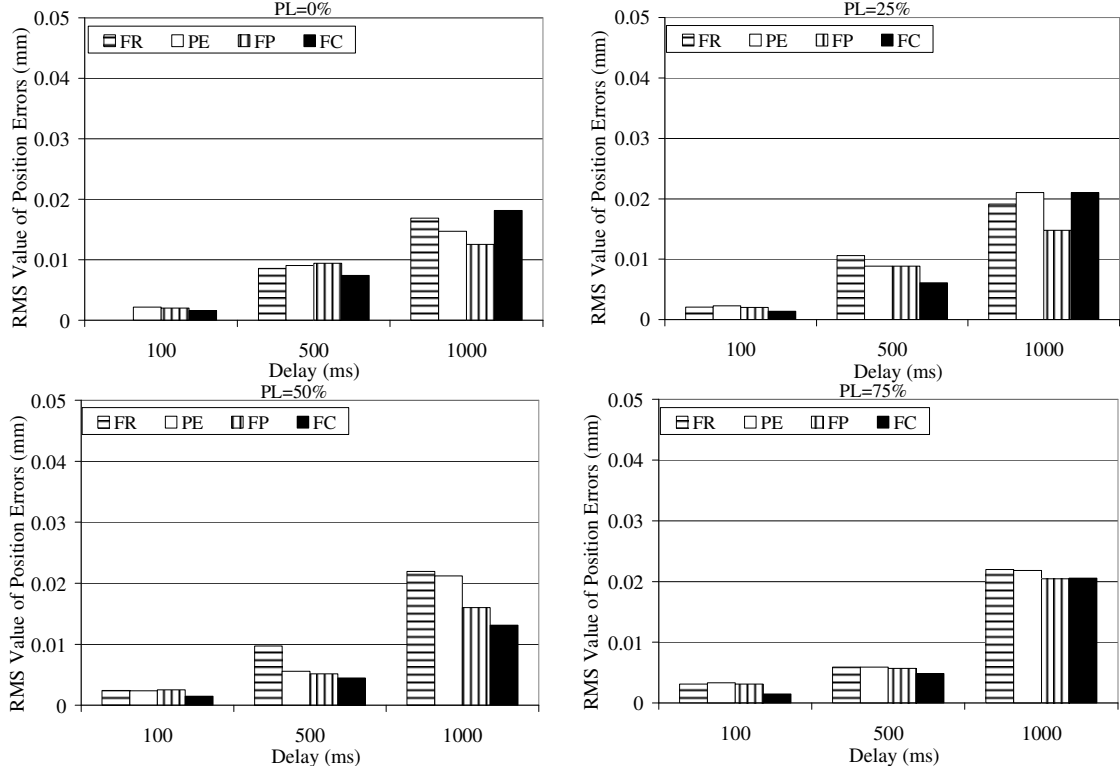


Figure 4.4 Effect of time delay on RMS value of position errors (number of runs=48).

4.2.3.2 Force tracking

The PE control scheme does not reflect the realistic interaction forces to the operator, because the force exerted by the haptic device, only relates to the position error between the master and slave as shown in Equation (4.2). Therefore, the evaluation of force tracking was conducted only for FR, FP and FC control schemes. In general, FR, FP and FC control schemes exhibited realistic transmission of the contact force from the slave site to the master site, and the operator was able to feel the environmental interaction in high fidelity, as illustrated in Figure 4.5. In order to facilitate visual comparison, the master force is scaled by a scaling factor. This factor is defined for all controllers by dividing the mean value of force, generated at the haptic device, to the mean value of force generated at the hydraulic actuator.

As illustrated in Figure 4.5, response of the FC controller exhibits the largest force error as time delay increases. Although force error increased with increasing time delay, no obvious fluctuation is observed in the tracking signals of FR and FP control schemes. In addition, more oscillations is observed in FC control scheme with the increase of packet loss as compared to FR and FP schemes. Note that once contact between the actuator and the environment is established, the haptic device reflects the force.

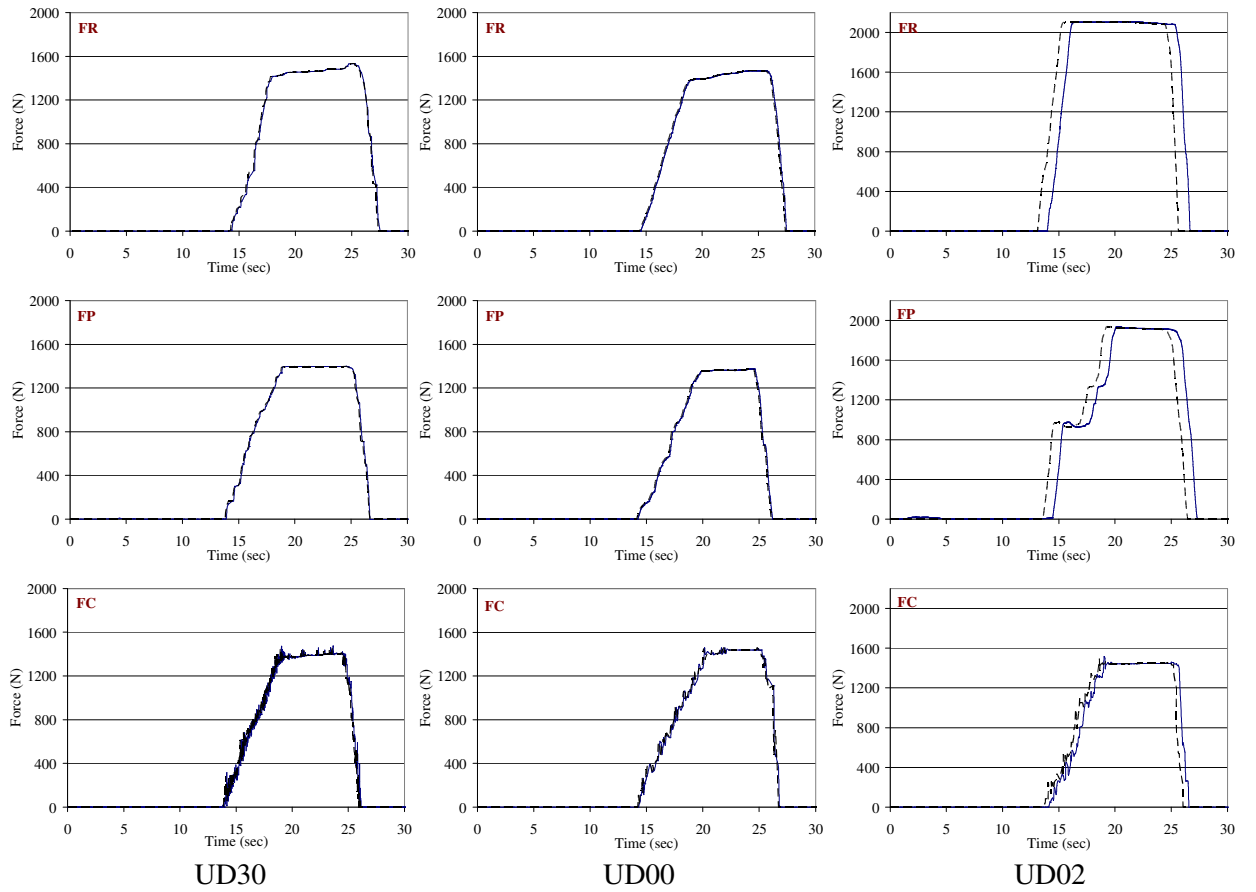


Figure 4.5 Forces produced by haptic device (solid line), and generated by the hydraulic actuator (dashed line), for all scenarios defined in Table 4.1.

In order to facilitate visual comparison, the master force was scaled by the scaling factor obtained by dividing the mean value of forces generated at the haptic device, by

the mean value of forces generated at the hydraulic actuator. Figure 4.6 depicts the effect of different constant time delays and packet losses on RMS values of tracking force errors ($F_m - F_s$). Error of force tracking is defined as the difference between the force generated at the actuator end-effector and the scaled version of the haptic device force. As shown in Figure 4.6, an increase in time delay increases tracking force error for FR, FP and FC control schemes. With respect to the effect of packet loss, the RMS values of force errors slightly increased in FR control scheme. However, for FP and FC control schemes, no conclusion can be drawn.

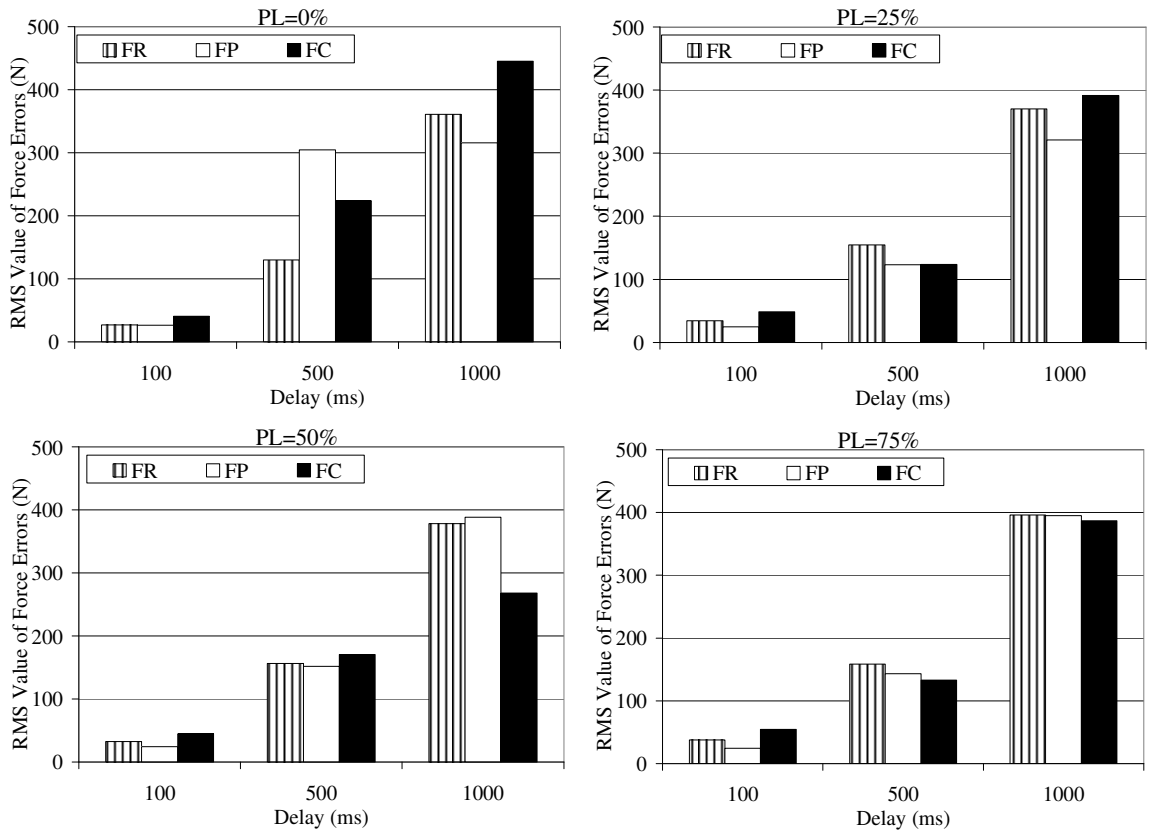


Figure 4.6 Effect of time delay on force tracking error for PL=0%, 25%, 50% and 75%.

4.2.3.3 Discussions

In conclusion, long time delay, in the communication channel, was observed to increase tracking errors irrespective of the type of control schemes used. Clearly, time delay in the communication channel does not allow information exchanges between the master and slave sites in a timely fashion. The control schemes examined here are not equipped with a predictor. Thus, in the presence of time delay, the actuator did not respond to the command from the master as it should be. This resulted in increased position and force tracking errors. The packet loss, on the other hand, was found to impact the quality of tracking (Figure 4.2 and Figure 4.5) and increased oscillations on the response. Loss of information in the control loop caused the control schemes being unable to generate proper signals resulting in jittery response between the master and the slave.

Figure 4.7 illustrates the control signals for the three cases UD30, UD00 and UD02. In general, the control signals of all control schemes were found to be within a reasonable range and not saturated. As observed, for the FC scheme, the control signal is larger than other schemes. The oscillations originate from the controller effort to compensate for errors appearing in the teleoperated system. It is well-established that when the time delay or packet loss is large enough in the communication channel, the stability of a bilateral teleoperated system cannot be guaranteed [101, 13]. In this study, the stability of the system is calculated solely based on observation similar to approach employed by Rodríguez *et al.* [57]. Experimental results showed that the system is observed to be stable under all network scenarios, though some fluctuations around actual trajectory are noticed. However, large values of delays or packet losses may destabilize the system.

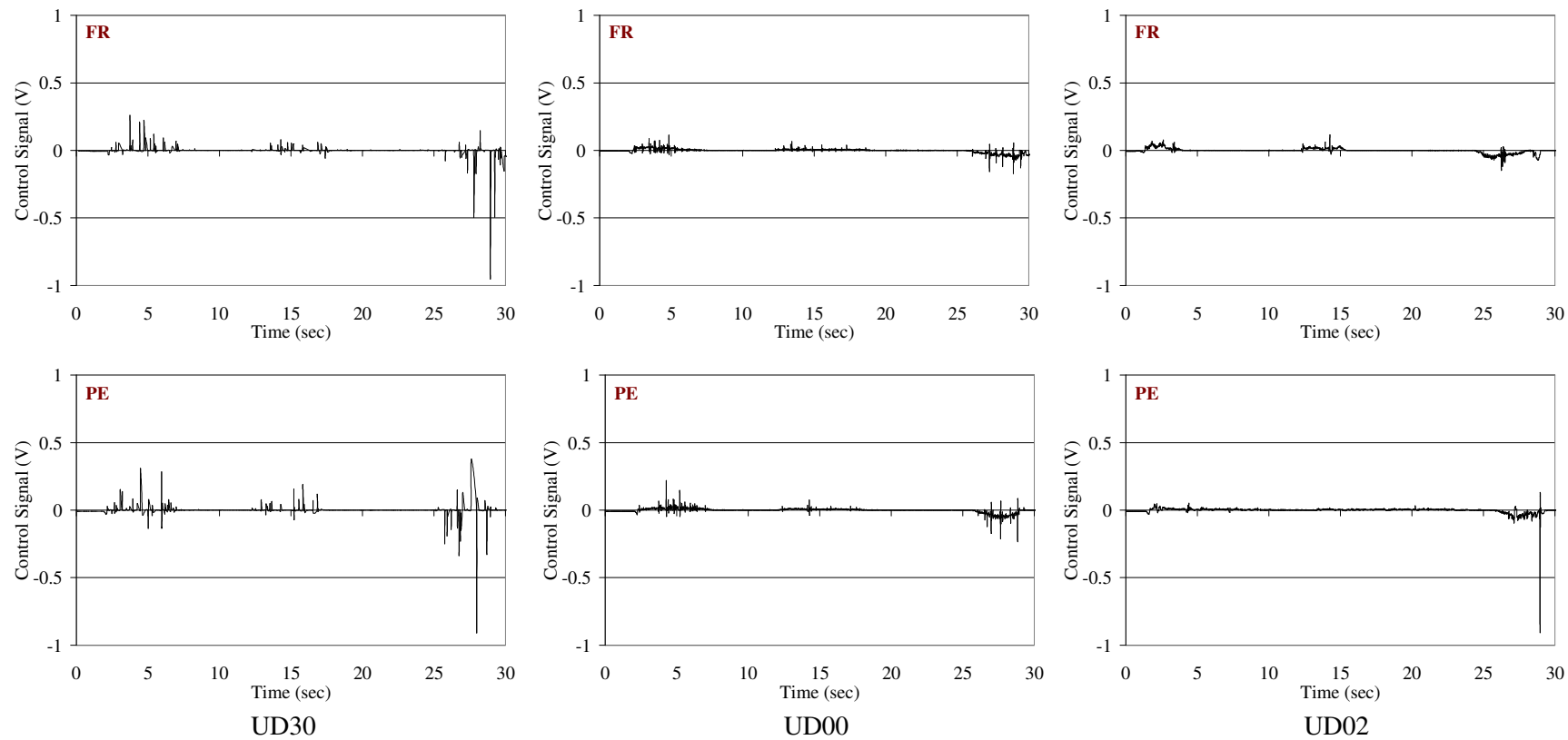


Figure 4.7 Control signals: TD=100 ms and PL=75% (UD30), TD=100 ms and PL=0% (UD00), and TD=1000 ms and PL=0% (UD02).

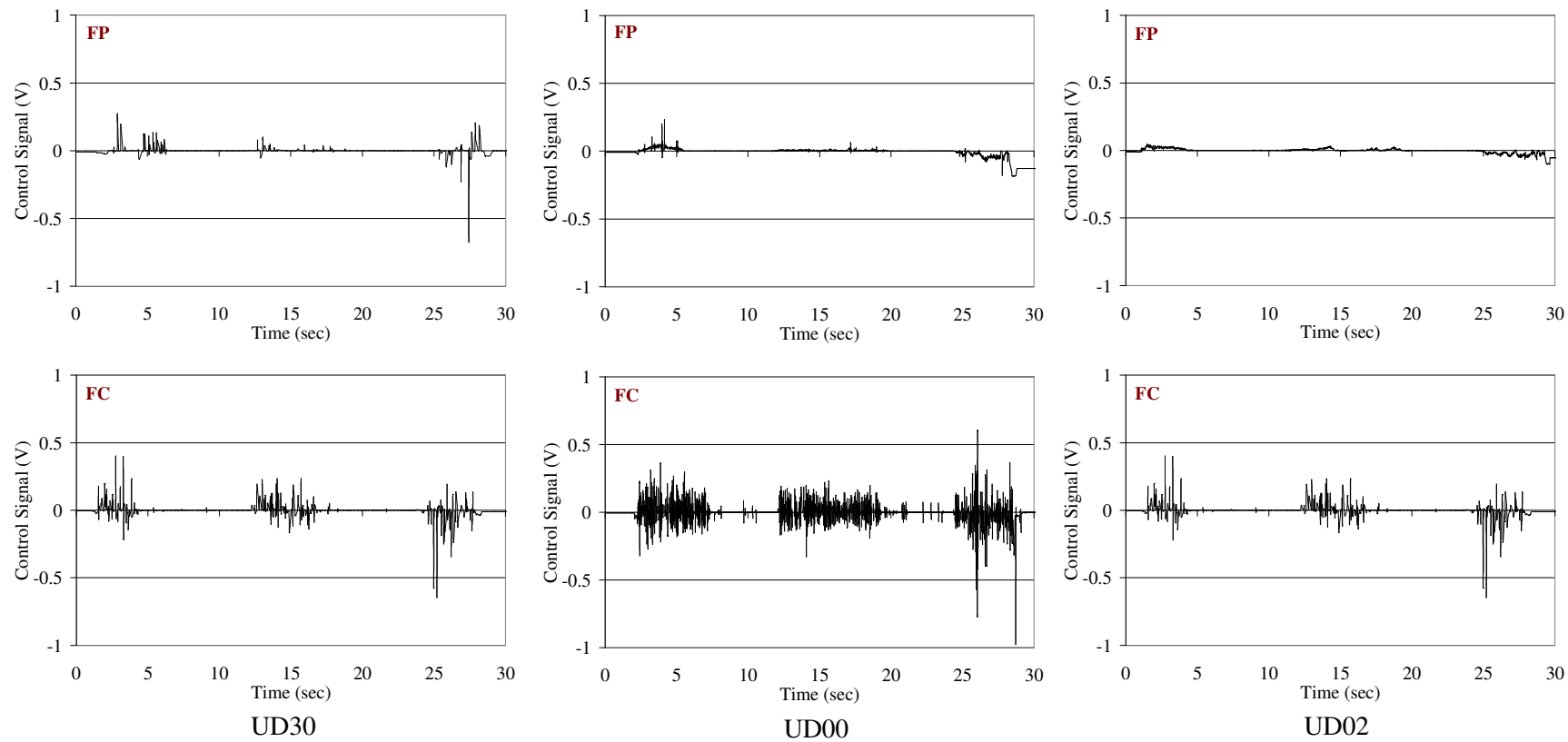


Figure 4.7 (Contd.) Control signals: TD=100 ms and PL=75% (UD30), TD=100 ms and PL=0% (UD00), and TD=1000 ms and PL=0% (UD02).

4.2.3.4 Perceived stiffness

Figure 4.8 and Figure 4.9 show the effect of constant time delays and packet losses on the perceived stiffness. During the constrained motion, the perceived stiffness is defined as the ratio of force generated by the haptic device (F_m) to the environment deflection, $F_m/(x_m - x_o)$ (see Figure 3.2). The perceived stiffness was calculated in frequency domain using Fast Fourier Transform (FFT). The arrows on vertical axes indicate the actual stiffness of the spring used in experiments for constrained motion ($k = 45 \text{ kN/m}$).

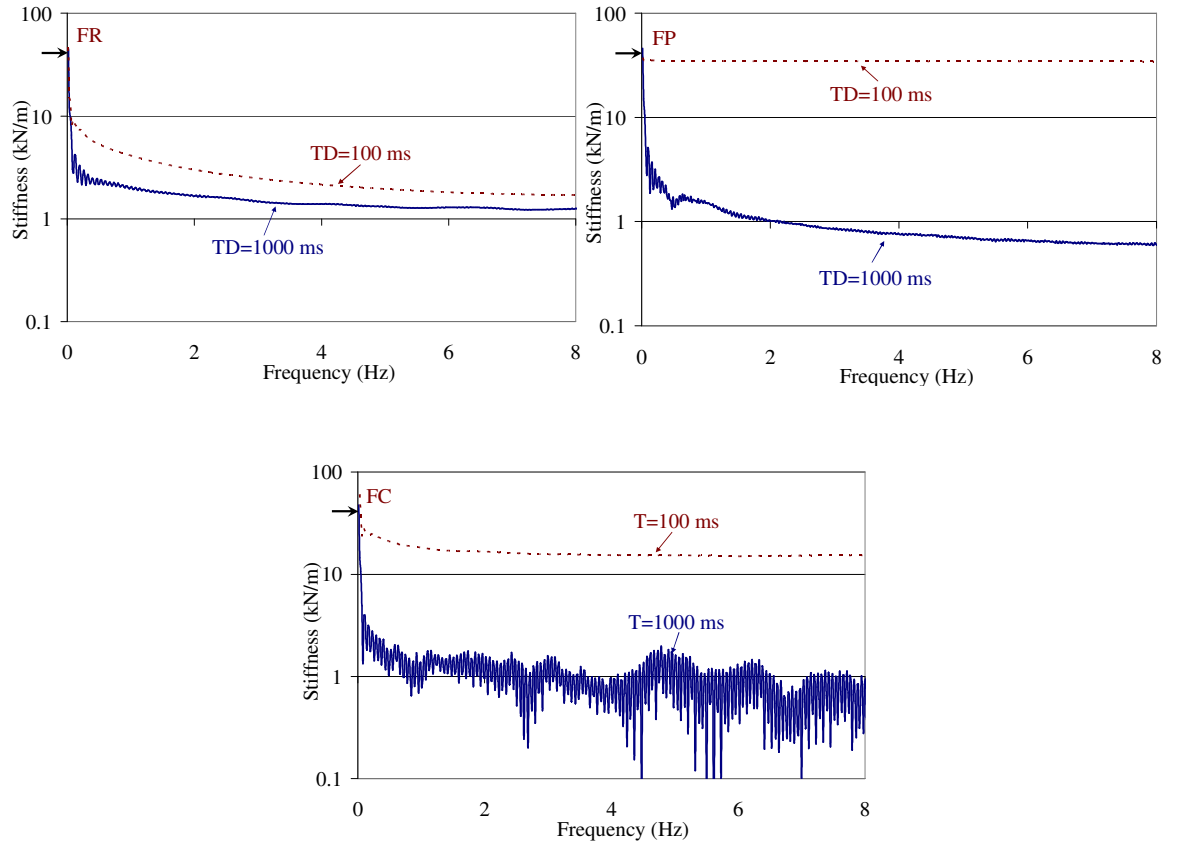


Figure 4.8 Effect of time delay on stiffness perceived by operator for PL=0%, TD=1000 ms (solid line) and PL=0%, TD=100 ms (dashed line). Arrows indicate actual stiffness of spring.

With reference to Figure 4.8 and Figure 4.9, when the stiffness at zero frequency is close to the stiffness of the spring in the model, it implies that the teleoperated system is transparent. Results were investigated for all control schemes except PE which is not able to provide a realistic stiffness. As illustrated in Figure 4.8 and Figure 4.9, the stiffness decreases as the time delay and packet loss increased. This implies that FR, FP and FC control schemes could not provide realistic stiffness to operator's perception with respect to changes in time delay and/or packet loss.

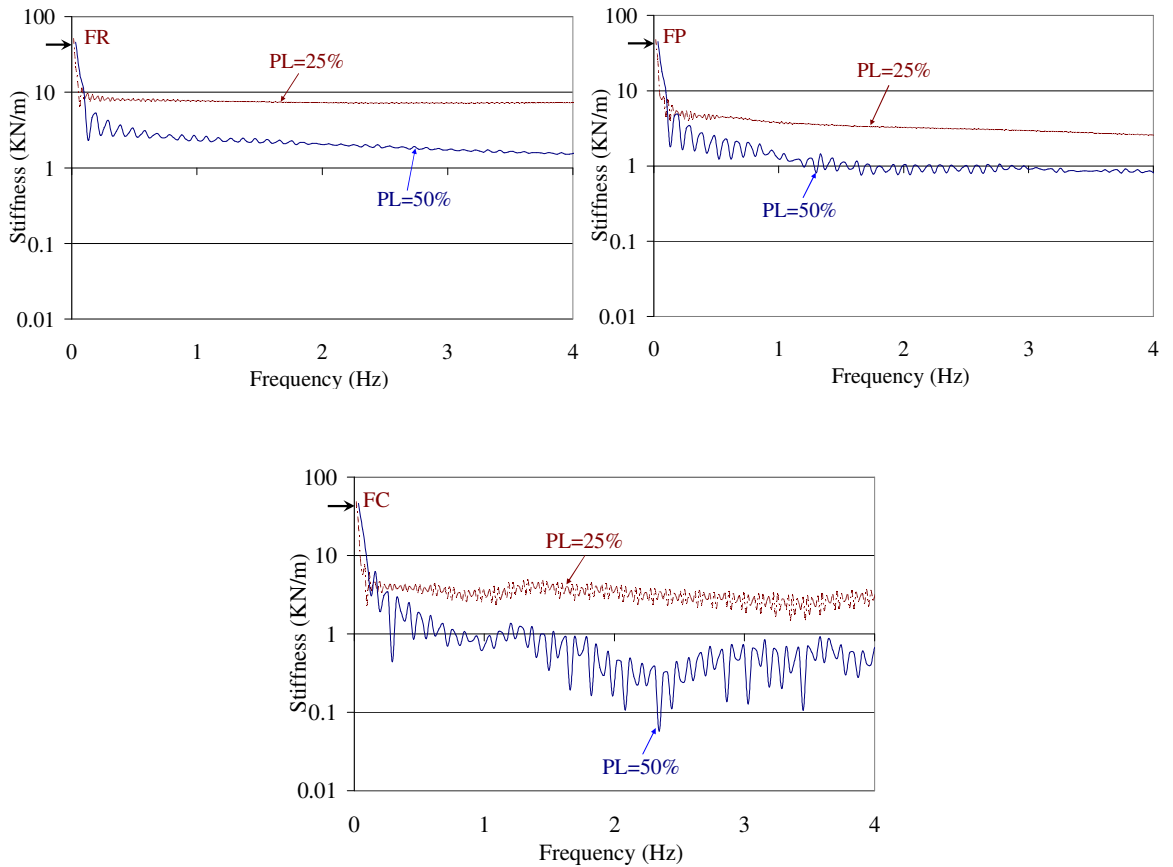


Figure 4.9 Effect of packet loss on stiffness perceived by operator for PL=50%, TD=100 ms (solid line) and PL=25%, TD=100 ms (dashed line). Arrows indicate actual stiffness of spring.

4.3. Performance Evaluations Under Wireless Channels

4.3.1. Implementation of wireless channel

The NS2 simulator is employed to investigate how well the teleoperated hydraulic actuator performs when the master and slave are wirelessly connected as in an outdoor environment. The study, conducted by Ivanov *et al.* [98], has shown that the NS2 wireless simulation can accurately reflect a real WiFi with a static environment and a simple obstruction model. Since future applications fall within this category, the simulation of wireless channels allows reflecting performance of the system in the field. Some inaccuracies in modeling may occur due to automatic data rate selection of wireless cards and processing delays of the operating system that are not considered in NS2 [102].

The NS2 supports the simulation of wireless networks using the IEEE 802.11 standard, which is a commonly used standard for communication in Wireless Local Area Networks (WLANs). The wireless experiments focus on investigating the effect of changes in parameters of the radio propagation model on performance of the teleoperated system [103]. One of the common radio propagation models is the shadowing model. The NS2 shadowing model computes the received power as a random variable due to multipath propagation effects in which the average received power is assumed to decrease logarithmically with distance. The shadowing model consists of two parts: first part predicts the mean received model and the second part reflects variations of this power. The power received by a receiver antenna (P_r), at a distance d from a transmitter antenna, is expressed by Friis free space equation [104],

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (4.9)$$

where P_t and G_t are the transmitter antenna power and gain, respectively. The receiver antenna gain and the wavelength are denoted by G_r and λ . L is the system loss factor which is not related to propagation ($L \geq 1$). Note that d represents the distance between the master and slave sites. Equation (4.9) is only applicable for distances that are shorter than what is used in practice, and within the far-field (Fraunhofer region) of the transmitter antenna [104].

In practice, the surrounding environment clutter may vastly be different for the same distance between the master and slave sites. Therefore, the received power is represented as a random and distributed log-normally function (normal in dB), at any distance of d , and expressed as follows [104]:

$$P_r(d) = 10^{X_\sigma} P_r(d_0) \left(\frac{d}{d_0} \right)^{-n} \quad (4.10)$$

or,

$$[P_r(d)]_{dB} = [P_r(d_0)]_{dB} - 10n \log \left(\frac{d}{d_0} \right) + X_\sigma \quad (4.11)$$

where n and d_0 are the path loss exponent and reference distance, respectively. $P_r(d_0)$ denotes the received power for a given d_0 , and is calculated using Equation (4.9). X_σ represents a Gaussian random variable with zero mean value and standard (shadowing) deviation of σ (in dB) [105]. Furthermore, n and σ are computed from measured data. Empirical measurements of coefficients n and σ , for a number of wave propagation cases, are given in [104]. For example, for offices with hard partition the values of n and σ are 3 dB and 7 dB, respectively.

In wireless communication systems, a target minimum received power level (P_{min}) is defined below which performance of the teleoperated system becomes unacceptable, *i.e.*

the system exhibits instability and/or poor transparency. The probability that the received signal level will fall below P_{min} is calculated from cumulative distribution function (cdf) using Equation (4.12) or (4.13).

$$Prob[P_r(d) \leq P_{min}] = Prob \left[[P_r(d_0)]_{dB} - 10n \log \left(\frac{d}{d_0} \right) + X_\sigma \leq [P_{min}]_{dB} \right] \quad (4.12)$$

or,

$$Prob[P_r(d) \leq P_{min}] = Prob \left[X_\sigma \leq 10n \log \left(\frac{d}{d_0} \right) - [P_r(d_0)]_{dB} + [P_{min}]_{dB} \right] \quad (4.13)$$

More specifically, $Prob[P_r(d) \leq P_{min}]$ indicates the probability of dropping a packet.

Using Equation (4.13), a study was first performed to find the probability of dropping a packet. In this set, P_t changed from 30 mW to 90 mW (10 typical values). P_{min} and n were set to -70 dB and 2.7 dB, respectively. The values of G_t and G_r were set to 2 dBi. The system loss constant, L , was equal to 1. Moreover, d_0 was set to 1 m, which is a value typically used for low-gain antennas for the considered frequency [104].

As shown in Figure 4.10, by increasing the distance, the probability for dropping a packet increases. Moreover, at a certain distance, the packet loss increases when a router with lower antenna power is chosen. The dashed arrow indicates the direction of increasing the antenna power (from 30 mW to 90 mW). Assuming a known obstruction ($n=2.7$) and a given antenna transmission power ($P_t=90$ mW), the packet loss of 40% is desirable. To find the corresponding distance (d), a horizontal line, which passes the packet loss of 40%, intersects the distribution diagram shown in Figure 4.10. The intersection point gives the distance of 95.2 m. It means any distance less than 95.2 m is probable to generate a packet loss of less than 40%, or packet received more than 60%. The results, shown in Figure 4.10, are in accordance with the results obtained from the NS2 software.

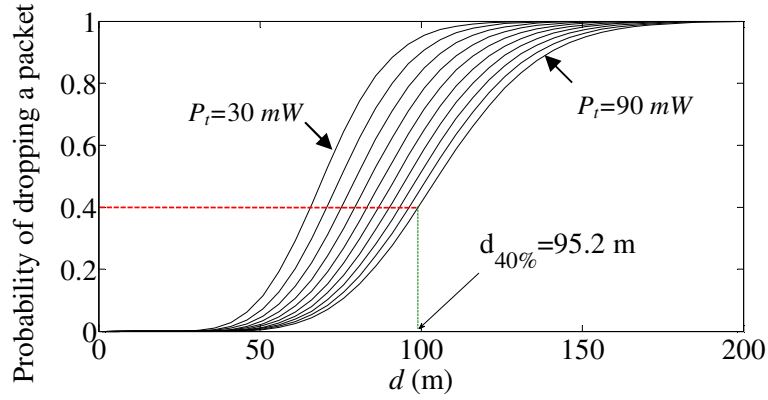


Figure 4.10 Probability of dropping a packet when $\sigma=4$ and $n=2.7$.

Table 4.2 shows the parameters set in network simulation for this study. The same values are also used to emulate the wireless network in Section 4.3.4.

Table 4.2. General wireless simulation parameters.

Parameter	Value
Channel bandwidth	11 <i>Mbit/s</i>
Contention window size	1-31
Short retry limit	2
long retry limit	1
Packet size	50 <i>bits</i>
Packet interval	2 <i>ms</i>

4.3.2. Establishing maximum allowable delay and packet loss

Two sets of experiments are performed in order to find the performance charts of the hydraulic actuator. The designed tests aim at identifying the maximum values of packet loss and time delay that do not affect the quality of position and force tracking signals. It is then followed by constructing a set of performance charts on the basis of identified loss and delay thresholds. Since time-varying delay and time-varying packet loss are two

main phenomena occurring in the wireless communication channels, the performance of the teleoperated system was first investigated under different combinations of time-varying delays and packet losses. The simulation of hydraulic actuator, interacting with a virtual spring (as described earlier in Section 3.2.1) was employed at the slave site, for the tests.

During the tests, the three computers, that serve as master, slave and network emulator respectively, are connected in a local area network through an Ethernet hub. Both the master and slave computers are set to send packets to the NS2. The NS2 changes the source and destination addresses of any incoming packets such that packets sent from the master site are forwarded to the slave site and *vice versa*. Thus, NS2 controls when packets are received by the master and slave sites. To ensure that the experiment can be repeated multiple times with the same network conditions, the network simulation has to be synchronized with the master and slave. To accomplish this, the simulator checks the packet data for the ready packet signal being transmitted by the slave each time the experiment starts.

In all tests, the hydraulic actuator was guided by the PHANToM Omni haptic device. The system was operated by the hybrid scheme, Equation (4.3), which was shown in Section 4.2 to have good performance (as compared to other tested schemes) in the presence of constant delay and packet loss. In each test, the operator was asked to follow a defined trajectory given in Figure 4.11. As observed, the desired trajectory was to move the actuator back and forth. This trajectory included moving the actuator in both free and constrained motions. In free motion, the hydraulic actuator was not in contact with any virtual environment. The actuator interacted with the environment emulated by a linear

spring of 45 kN/m stiffness in constrained motion. The total time of each motion cycle depended on the operator's hand speed, and took 1 to 4 seconds. Typical tests, reported in the following section, were performed with the actuator speed of about 10 cm/s and without causing saturation in the control signal [106]. Although the operator was asked to move the haptic implement from $x_m = 80 \text{ mm}$ and $x_m = 130 \text{ mm}$; since there was no physical or virtual constraint, in some trials, the operator exceeded the determined displacement interval.

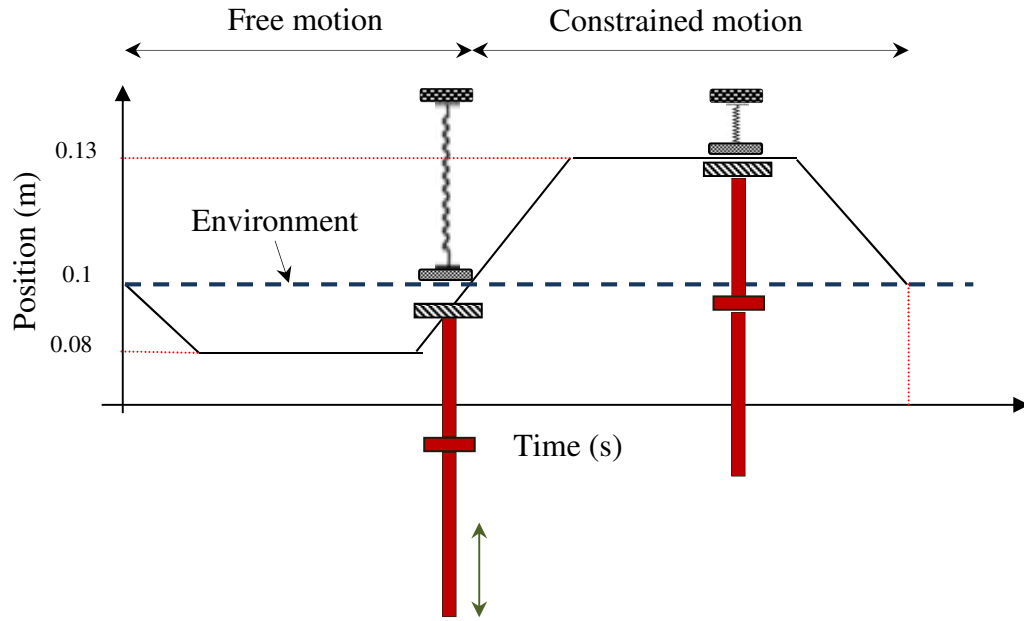
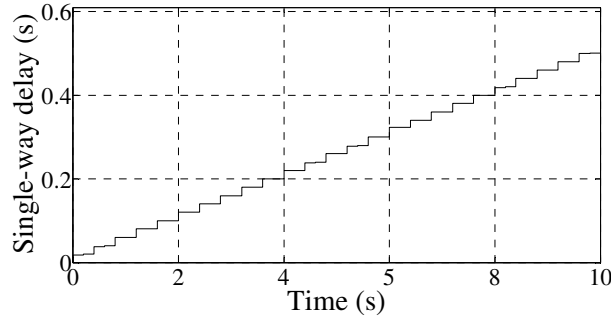


Figure 4.11 Typical trajectory of hydraulic actuator coordinated by haptic device.

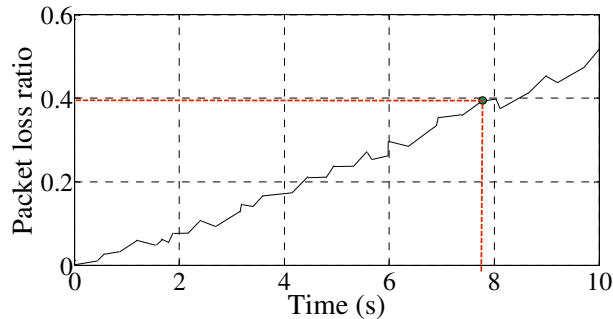
The profiles for the delay and loss were generated using the NS2 simulator. Although the profiles do not accurately reflect the network conditions encountered in practice, they were used to observe how the response of system changes while delay and packet loss are changing over time. Only the results of two typical scenarios are presented in details (see Figure 4.12). For each scenario, 10 trials were conducted. In the first scenario, the packet

loss was set to 0% and the round trip time delay gradually increased at every 400 ms from 0 ms to 1000 ms. In the second scenario, time delay was set to 150 ms and the packet loss increased from 0 to about 50%. The delay of 150 ms was the minimum delay that was achieved in the bilateral control of the hydraulic actuators, and was obtained by directly connecting the master and slave sites.

The experimental results were qualitatively analyzed by observing how well position and force signals at the slave and master sites are tracked. The random packet loss profile was generated by drawing a uniformly distributed random number for each packet and dropping those above the current threshold. For this typical test, the threshold was chosen such that packet loss percentage increased by roughly 10% every 2 seconds (see Figure 4.12b).



(a) First scenario (time-varying delay)



(b) Second scenario (time-varying packet loss)

Figure 4.12 Network characteristics (single-way delay and packet loss) used to find the maximum allowable delay and packet loss.

Figure 4.13a and Figure 4.14a illustrate position tracking results during free and constrained motions, and under the first and second network scenarios, respectively. Figure 4.13a shows that by increasing the time delay, the steady-state position error increased; however, the slave still followed the operator's hand motion smoothly. With reference to Figure 4.14a, it is evident that the response of the slave actuator became oscillatory when the packet loss increased. As observed, the position signal fluctuated at about 7.7 s that has the packet loss of 40% (see Figure 4.12b) and is expected to become more oscillatory for packet losses more than 40%, as observed in Figure 4.14a and Figure 4.14b.

The tested teleoperated system exhibited realistic transmission of contact force from the slave site to the master site. The operator was able to feel the environment interaction as well as position error at the actuator end-effector in high fidelity (see Figure 4.13b and Figure 4.13b). As observed in Figure 4.14b, the force signal showed oscillation by increasing the packet loss. The reason is that the generated force at the haptic device partially originates from the position error. In conclusion, according to the experiments, the position and force signals of the teleoperated hydraulic actuator had good tracking when the round trip delay and packet loss increased up to 1000 ms and 40%, respectively.

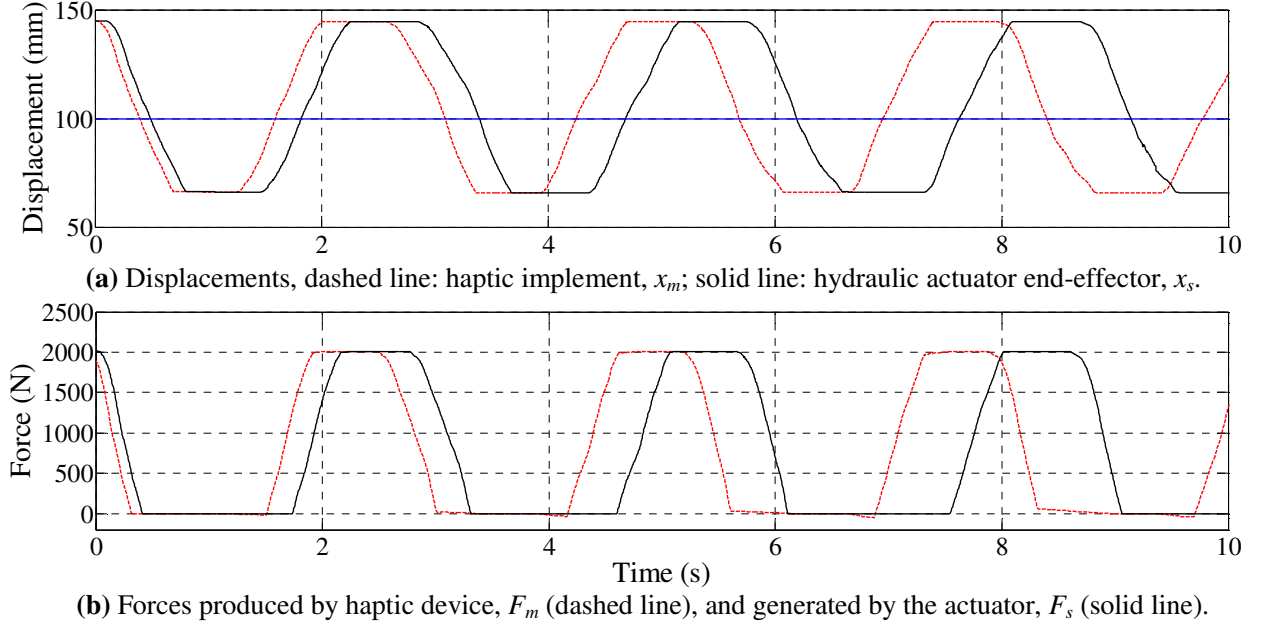


Figure 4.13 Experimental results pertaining first network scenario using PHANToM device, NS2 simulator and simulation of hydraulic actuator; (a) displacements at master and slave sites; (b) forces produced by haptic device.

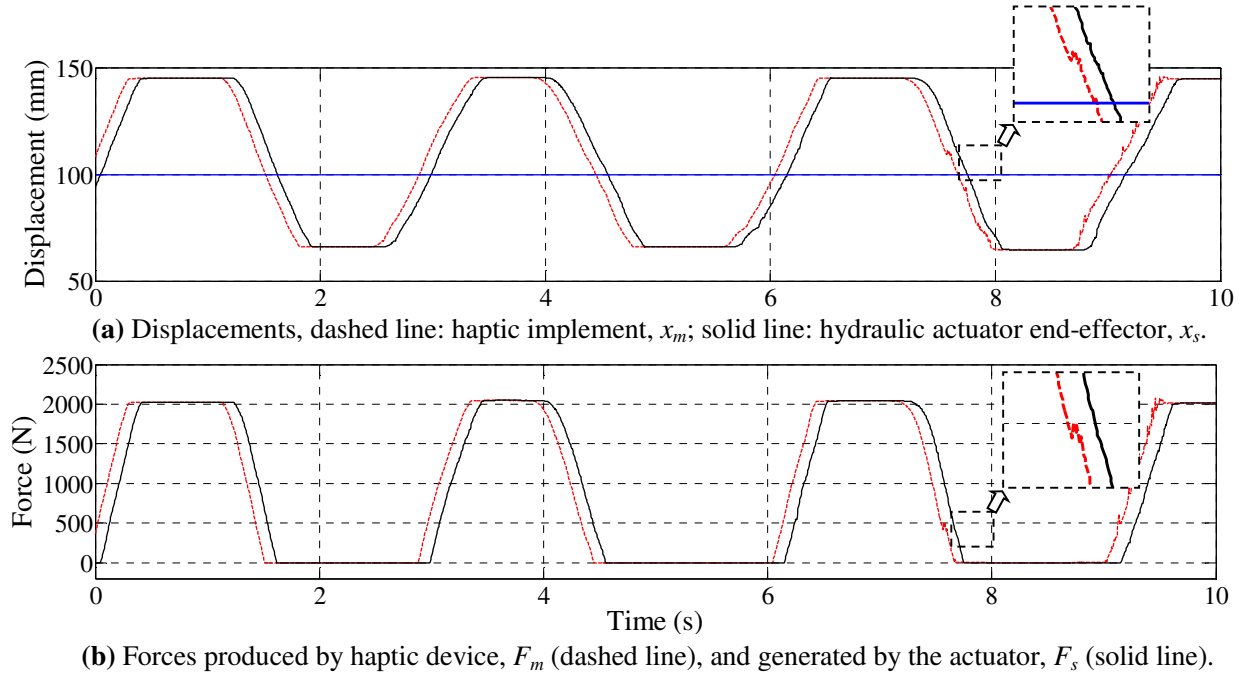


Figure 4.14 Experimental results pertaining second network scenario using PHANToM device, NS2 simulator and simulation of hydraulic actuator; (a) displacements at master and slave sites, (b) forces produced by haptic device.

4.3.3. Constructing performance charts

A set of experiments in a field trial (see Figure 4.15) was conducted to identify the ranges within which the network parameters change in real field. In this set of tests, the master site was stationed inside a van, and the slave PC was located on top of the bucket of a crane close to a 230kV live-line. By driving the van around, it was possible to create various scenarios of communication channels in terms of distance and obstruction. The distance between the master and slave sites varied from 40 m to 120 m. Results of this

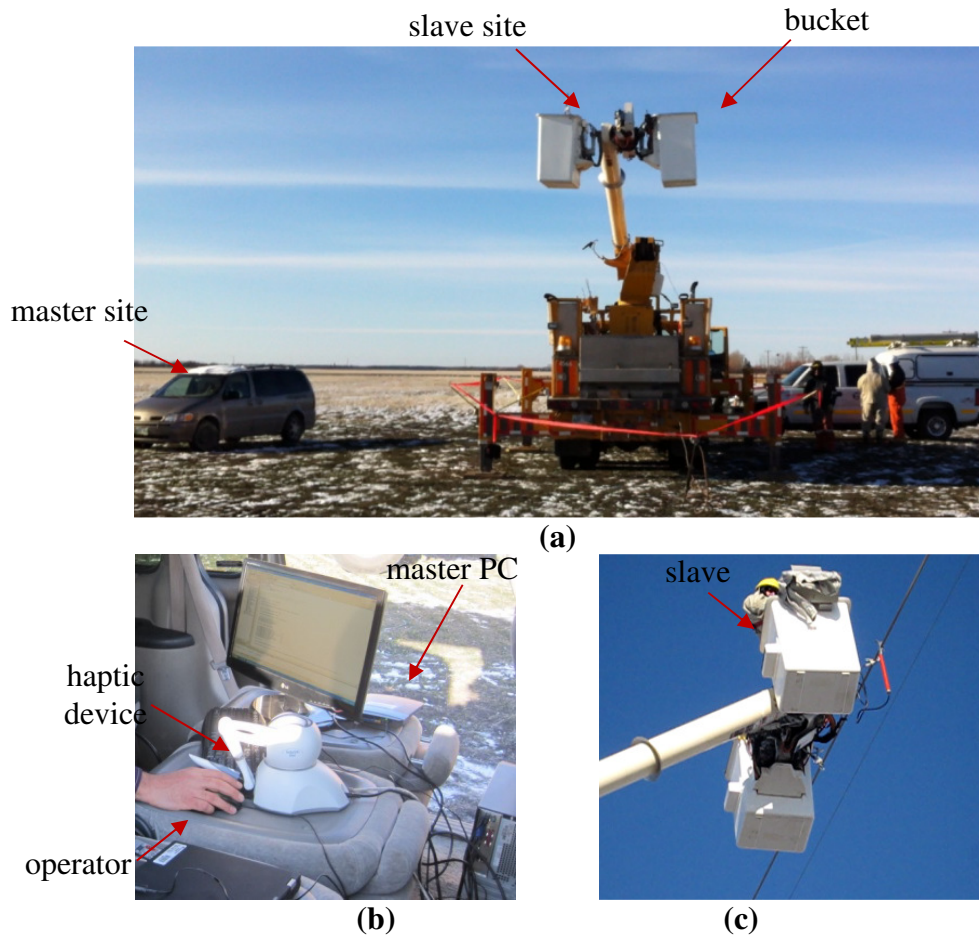


Figure 4.15 (a) Experimental field test setup; (b) master site: operator, haptic device, master PC, and wireless router; (c) slave PC.

preliminary study showed that time delay was constant and remained below 1000 ms; and therefore, did not affect the performance of the tested teleoperated system [42].

As resulted from the field test, the value of packet loss was almost constant. However, by increasing the distance or changing the environment obstruction, packet losses of more than 40% were noticed. It is established that networks having packet loss of more than 40% do not guarantee good performance for the system under investigation. Therefore, any packet loss below 20% is considered very reasonable in terms of producing high quality of tracking. As a result, three regions are defined: acceptable (packet loss is less than 20%), marginal (packet loss is between 20% and 40%), and unacceptable (packet loss more than 40%). Note that the acceptable 20% packet loss is conservatively chosen

Using the approach shown in Figure 4.10, a lookup table was then constructed (see Table 4.3). In this table, for a given pair of n and P_t , the distances, that the network has packet losses of 20% and 40%, were found. An example is given in the middle column of Table 4.3. The lookup table can also be presented in the form of a set of performance charts shown in Figure 4.16. These values can change, and new table can be established, according to the technical specifications of the router. In Figure 4.16, A and U stand for “Acceptable” and “Unacceptable” regions, respectively. Area between two curves belongs to marginal region.

Table 4.3 Lookup table of network parameters for hydraulic actuator. G_t and G_r are set to 2 dbi.

$n=2.0$			$n=2.3$			$n=2.7$			$n=3.0$			$n=3.3$		
P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)
30	212.7	251.2	30	98.9	114.1	30	55.7	63.1	30	35.6	39.8	30	24.9	27.5
37	235.1	277.8	37	107.8	124.3	37	60.0	68.0	37	38.1	42.5	37	26.4	29.2
43	255.6	302.0	43	115.8	133.5	43	63.9	72.4	43	40.2	45.0	43	27.8	30.7
50	274.6	324.4	50	123.1	142.0	50	67.4	76.4	50	42.2	47.2	50	29.0	32.1
57	292.3	345.3	57	129.9	149.8	57	70.6	80.0	57	44.0	49.2	57	30.1	33.3
63	309.0	365.1	63	136.2	157.1	63	73.6	83.5	63	45.6	51.0	63	31.1	34.4
70	324.9	383.8	70	142.2	164.0	70	76.5	86.7	70	47.2	52.8	70	32.1	35.5
77	340.0	401.7	77	147.8	170.5	77	79.1	89.7	77	48.7	54.4	77	33.0	36.5
83	354.5	418.8	83	153.2	176.7	83	81.6	92.5	83	50.0	55.9	83	33.8	37.4
90	368.4	435.2	90	158.4	182.7	90	84.0	95.2	90	51.4	57.4	90	34.6	38.3
$n=3.7$			$n=4.0$			$n=4.3$			$n=4.7$			$n=5.0$		
P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)	P_t (mW)	$d_{20\%}$ (m)	$d_{40\%}$ (m)
30	18.5	20.3	30	14.5	15.8	30	11.8	12.8	30	9.9	10.6	30	8.5	9.1
37	19.6	21.5	37	15.3	16.6	37	12.4	13.4	37	10.3	11.1	37	8.8	9.5
43	20.5	22.5	43	15.9	17.3	43	12.9	13.9	43	10.7	11.5	43	9.1	9.8
50	21.3	23.4	50	16.5	18.0	50	13.3	14.3	50	11.1	11.9	50	9.4	10.1
57	22.1	24.2	57	17.0	18.5	57	13.7	14.8	57	11.4	12.2	57	9.6	10.3
63	22.8	24.9	63	17.5	19.1	63	14.1	15.2	63	11.6	12.5	63	9.9	10.5
70	23.4	25.6	70	18.0	19.5	70	14.4	15.5	70	11.9	12.8	70	10.1	10.8
77	24.0	26.3	77	18.4	20.0	77	14.7	15.9	77	12.1	13.0	77	10.2	11.0
83	24.5	26.9	83	18.8	20.4	83	15.0	16.2	83	12.3	13.3	83	10.4	11.1
90	25.1	27.4	90	19.1	20.8	90	15.2	16.5	90	12.5	13.5	90	10.6	11.3

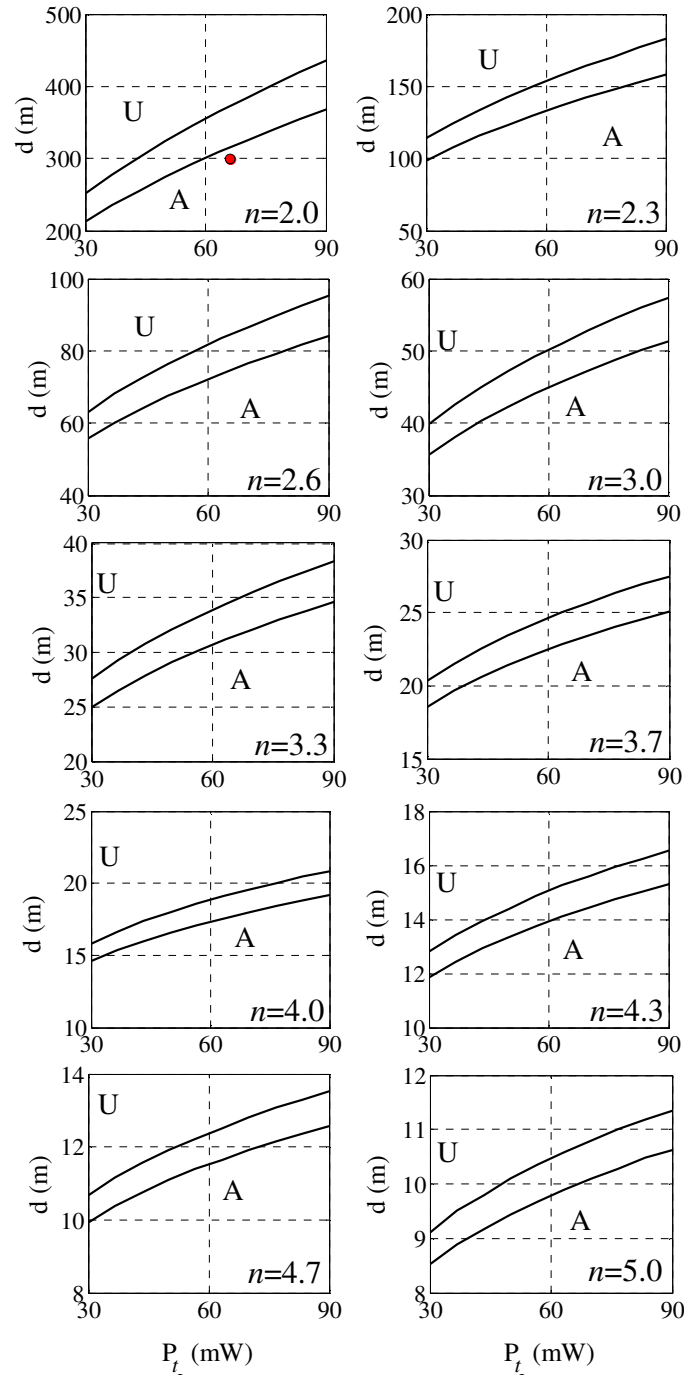


Figure 4.16 Performance chart of the guideline designed to select network parameters for hydraulic actuator.

Either Table 4.3 or Figure 4.16 can be used to select the router type and choose proper distance between the master and slave sites, in a known environment. For instance, in

live-line maintenance, when the slave robot works near line transmission lines in an environment without any obstacle ($n=2$) and the lineman controls the robot at a distance of 300 m, in order to have an acceptable quality of tracking, a router with the minimum antenna transmission power of 63 mW should be employed (see shaded raw in the first column of Table 4.3 and circle in Figure 4.16).

4.3.4. Further experimental validations

Two sets of validation tests were performed: (i) the slave PC runs a program simulating dynamics of the valve-controlled hydraulic actuator, and (ii) a real hydraulic actuator operates as the slave site. In total, $10(\text{trials}) \times 2(n) \times 2(P_t) \times 3(d) = 120$ experiments were conducted when the slave PC executed the hydraulic simulator. The chosen path loss exponents (n) were 2.3 and 3.0, and the antenna transmission powers (P_t) were set to 30 mW and 60 mW. For each pair of n and P_t , three distances (d) were selected from “acceptable”, “marginal”, and “unacceptable” regions. Network scenarios are shown in Table 4.4.

Table 4.4 Characteristics of network scenarios. A, M, and U show that scenario belongs to Acceptable, Marginal, and Unacceptable regions, respectively.

Network parameter	S01 (A)	S02 (M)	S03 (U)	S04 (A)	S05 (M)	S06 (U)	S07 (A)	S08 (M)	S09 (U)	S10 (A)	S11 (M)	S12 (U)
n	2.3						3.0					
P_t (mW)	30			60			30			60		
d (m)	80	100	128	120	140	170	25	35	42	40	45	52

As shown in Figure 4.17, the obstruction type, antenna power and distance did not change significantly the time delay. In other words, the time delays were almost the same and less than 1 ms in all scenarios, which is considered negligible as compared to total

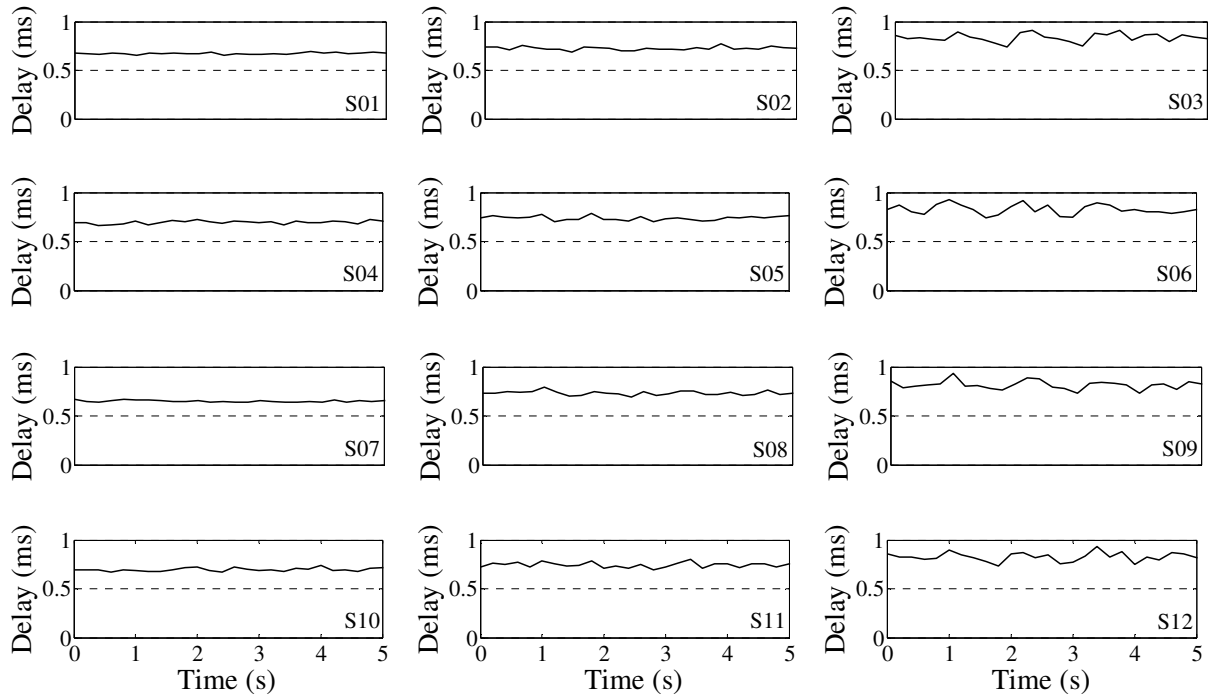


Figure 4.17 Variations of time delay over a 5-second period for scenarios defined in Table 4.4.

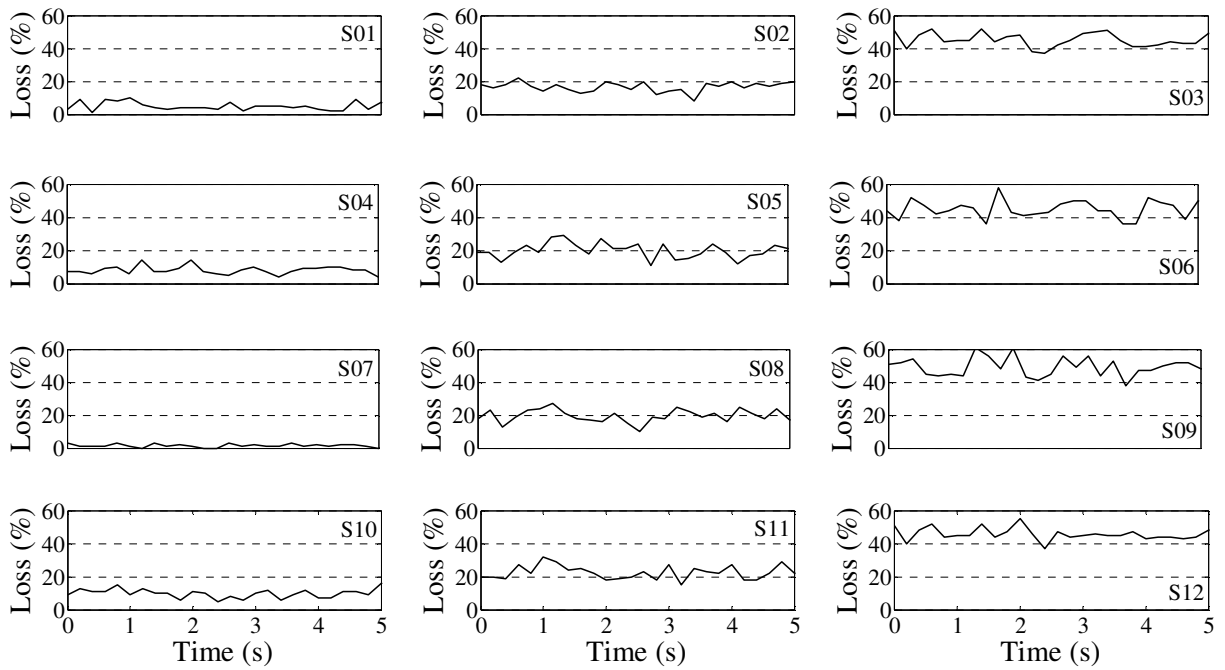


Figure 4.18 Variations of packet loss over a 5-second period for scenarios defined in Table 4.4.

time delay appeared due to computation time in system with simulated or real hydraulic actuator (150 ms). Figure 4.18 shows variations of packet loss during scenarios S01 to S12. With reference to Figure 4.10, given a pair of n and P_t , the mean value of packet losses becomes larger when the distance between the master and slave sites increases.

The first set of validation tests was conducted when the simulated hydraulic actuator was used as the slave manipulator because the use of real hydraulic actuator might jeopardize the experimental test rig when the system operates under “unacceptable” region. The validation was done for all 12 network parameters chosen within acceptable (S01, S04, S07 and S10), marginal (S02, S05, S08 and S11), and unacceptable (S03, S06, S09 and S12) regions (see Table 4.4). The stability of the system was investigated similar to the approach implemented in [40]. According to the experimental results, the system was observed to be stable under all tested network scenarios, however, some fluctuations around the actual trajectory were observed. After ensuring the system stability, the transparency of the system was examined.

Figure 4.19 illustrates the position response of the master device implement and the slave end-effector, for the first set of tests. As observed, the responses in both “acceptable” and “marginal” regions are good in terms of position tracking. Nevertheless, the system did not respond well when it worked in “unacceptable” region. The arrows in Figure 4.19 indicate that the simulated hydraulic actuator did not always follow the master position for experiments performed in “unacceptable” region. Similar observation is seen from the last column of Figure 4.20 for the force tracking signals. Figure 4.20 shows that the force signals, in all experiments, had good tracking, except for tests chosen from the “unacceptable” region. In general, the experiment (using a simulation

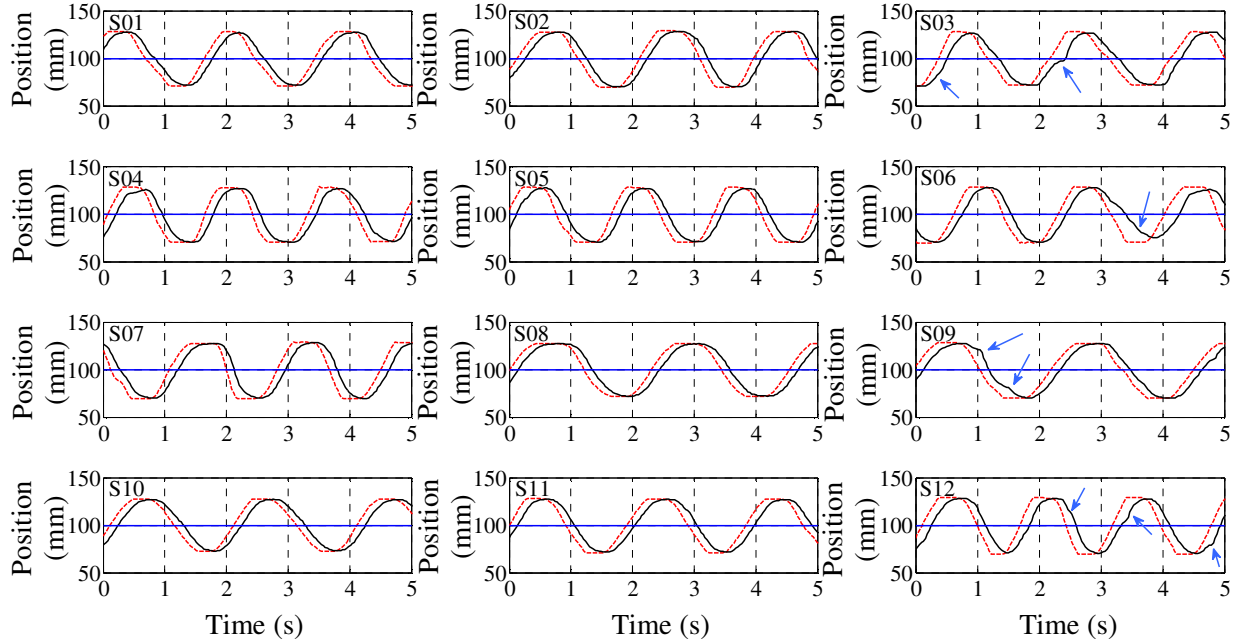


Figure 4.19 Position tracking of hydraulic actuator end-effector (dashed line), and haptic device implement (solid line) for scenarios S01 to S12.

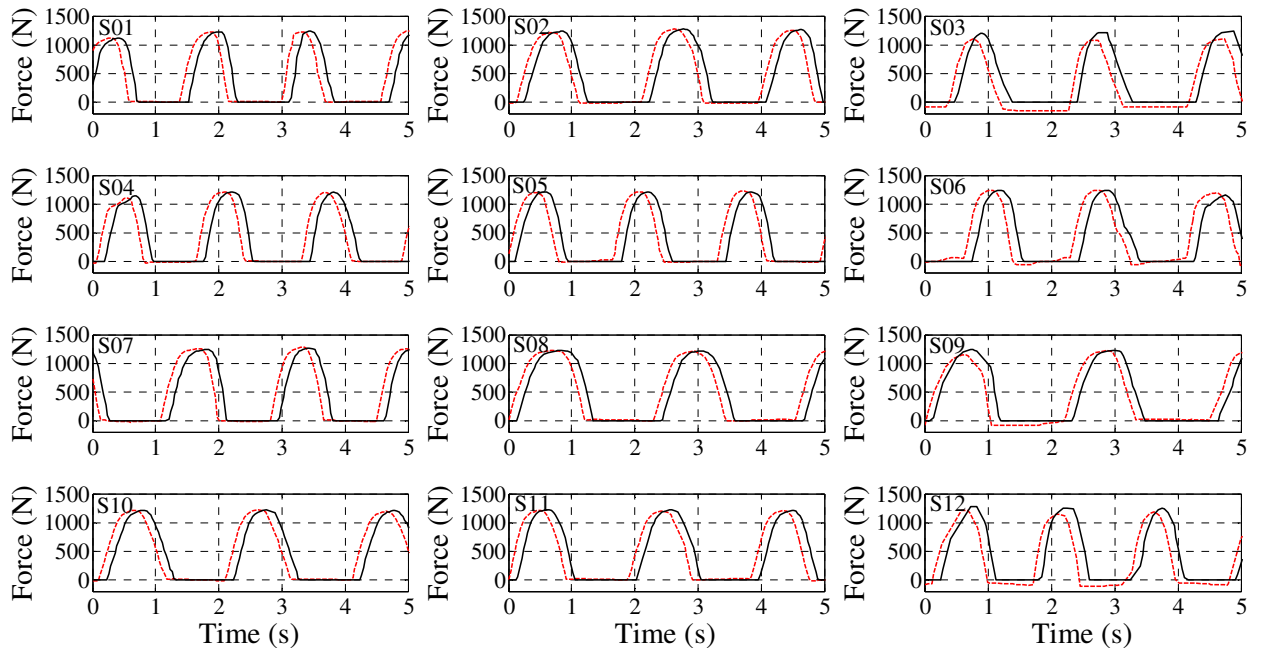


Figure 4.20 Forces produced by haptic device (dashed line), and generated by hydraulic actuator (solid line), for scenarios S01 to S12.

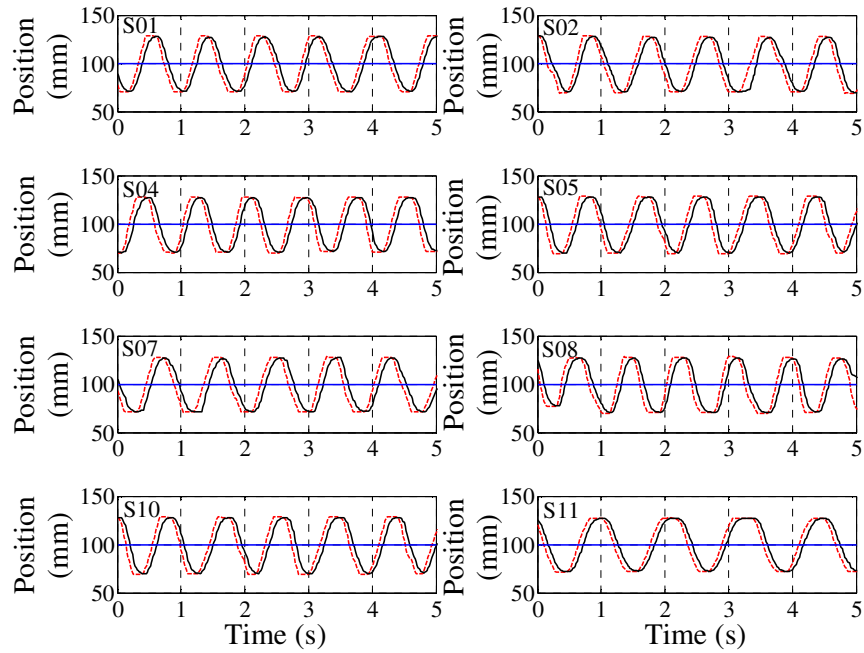


Figure 4.21 Position of hydraulic actuator end-effector (dashed line), and haptic device implement (solid line) under scenarios defined within acceptable and marginal regions.

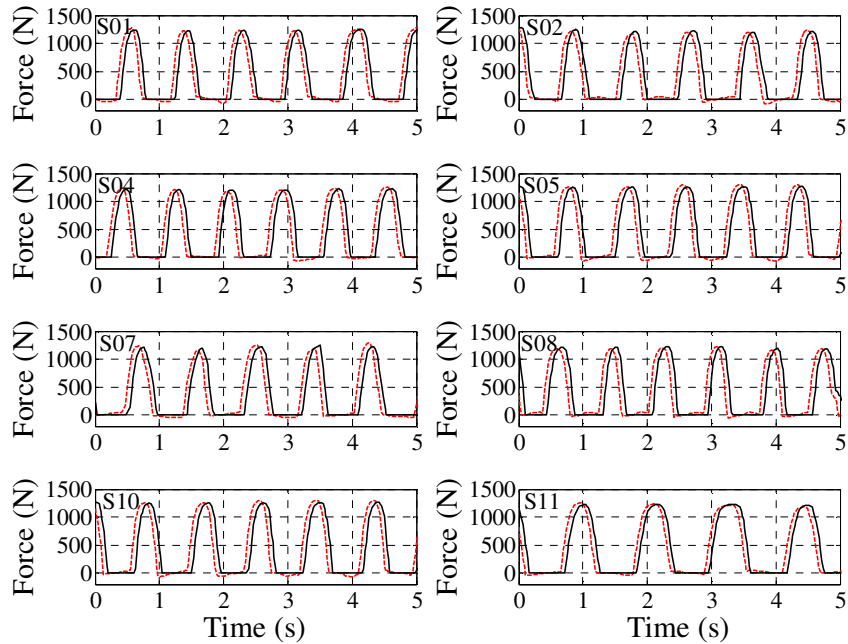


Figure 4.22 Force produced by haptic device (dashed line), and generated by the hydraulic actuator (solid line), for scenarios defined within acceptable and marginal regions.

model for hydraulic actuator) validated the effectiveness of the charts constructed for wireless control of hydraulic manipulators.

The second set of experimental validations was designed within the “acceptable” and “marginal” regions only (80 trial runs). In these tests, the hydraulic test rig, shown in Figure 3.2, was used. Typical position responses, within acceptable (S01, S04, S07 and S10) and marginal (S02, S05, S08 and S11) scenarios, are shown in Figure 4.21. As observed, the system performance is acceptable in these tested scenarios. Force signals are also depicted in Figure 4.22, which shows good force tracking in the system.

4.4. Summary

This chapter presented a comparative study of four schemes for bilateral control of a valve-controlled hydraulic actuator under two network parameters: time delay and packet loss for both dedicated and wireless channels. In the first set of experiments, four bilateral schemes were employed to investigate the effect of dedicated channels with constant packet loss and constant time delay. The schemes were position error, force reflection, combined force reflection and position error (hybrid), and four channels architectures. The goal was to investigate how well each scheme performs in control of hydraulic actuators and in the presence of constant time delays and/or packet losses. The criteria for evaluations were: (i) position tracking of the slave hydraulic actuator, (ii) force tracking of the haptic device and (iii), perceived environmental stiffness by the operator. The evaluations were performed on a set up consisting of a commercially available haptic device (master), a double-rod valve-controlled hydraulic actuator (slave), and an emulated communication channel. The setup provided a great opportunity to understand

the effect of delayed and lossy networks on a common system. Experimental results indicated that all control schemes worked stably for teleoperation control of hydraulic actuators for time delays up to 1000 ms and packet losses up to 75%. For an optimum performance, the control schemes have to be chosen depending on the specific application. For applications that need both force and position tracking functionality, and in the presence of time delay and/or packet loss in the communication channel, the hybrid scheme is the best choice. In applications where only position tracking is of interest, the position error scheme is recommended since it is simpler to implement.

The hybrid scheme was then chosen to evaluate the performance of the actuator when it operates under wireless communication channels. The evaluation was conducted using two indices: position tracking of the slave hydraulic actuator, and force tracking of the haptic device. Preliminary studies indicated the system was stable and had good tracking for time-varying delays up to 1000 ms and time-varying packet losses up to 40%. Using these results, a set of performance charts was constructed to select proper antenna transmission power of the router and distance between master and slave sites in the field. The charts define three regions, namely acceptable, marginal, and unacceptable. Each region allows different combinations of path loss exponent, antenna transmission power, and distance between the master and the slave sites. Further validation experiments were carried out on a setup comprising a PHANTOM Omni haptic device, and a single-DOF hydraulic manipulator. Table 4.5 and Table 4.6 summarize how network parameters influence the performances of the teleoperated system in both dedicated and wireless networks. The signs shown in this table indicate increasing ($\uparrow$), decreasing ($\downarrow$), no effect ($\cdots$) or no conclusion ($\circ$) on each of the evaluated criteria.

Table 4.5 Qualitative summary of time delay and packet drop effects on performance, dedicated channel.

Scheme	Network parameter	Position error	Force error	Perceived stiffness
FR	Time delay $\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$
	Packet loss $\uparrow$	...	$\uparrow$	$\downarrow$
PE	Time delay $\uparrow$	$\uparrow$	Not applicable	Not applicable
	Packet loss $\uparrow$	...		
FP	Time delay $\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$
	Packet loss $\uparrow$	...	$\circ$	$\downarrow$
FC	Time delay $\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$
	Packet loss $\uparrow$	...	$\circ$	$\downarrow$

Table 4.6 Qualitative summary wireless network setting effects on performance of system.

Scheme	Network parameter	Position error	Force error
FP	$n \uparrow$	$\uparrow$	$\uparrow$
	$P_t \uparrow$	$\downarrow$	$\downarrow$
	$d \uparrow$	$\uparrow$	$\uparrow$

CHAPTER 5

UNILATERAL AND BILATERAL CONTROLS FOR HYDRAULIC MANIPULATORS

5.1. Introduction

When a teleoperated manipulator is used for repetitive tasks, haptic virtual fixture force is a potential tool applied to the operator's hand to raise the level of safety and precision that an operator can achieve [107]. Within this context, the concept of virtual fixtures is used in several applications showing its effectiveness to improve accuracy and to decrease the task completion time for certain tasks [82]. However, although the virtual fixture force keeps the operator's hand on the defined virtual fixture path, accurate motion at the slave side still cannot be guaranteed. The position tracking of slave manipulator can easily be violated due to fast motion of the operator's hand at the master side, lack of responsiveness in actuation system, or poor quality of communication channel. Additionally, since hydraulic actuators exhibit significant nonlinear characteristics, the requirement of position tracking is generally more challenging in teleoperated hydraulic manipulators than that of their electromechanical counterparts

[108]. Specifically, as will be shown here, the position error at a slave hydraulic manipulator is beyond the controller response.

In this chapter, to alleviate the problem of position inaccuracy, the virtual fixture force (in unilateral mode) is augmented by a novel position referenced force augmentation scheme (in bilateral mode). Using this scheme, when position error appears at the manipulator end-effector, the augmentation force is applied to the operator's hand, and signals her/him to move slower. This slowed motion allows the hydraulic manipulator to catch up the master motion, *i.e.* reduce the position error arising from high speed tracking demands. Performance of the proposed scheme is evaluated by measuring the values of position errors at the master implement and the slave end-effector, and when the proposed scheme is applied by itself or combined with the virtual fixture concept. The experiments are conducted on the hydraulic telemanipulator for performing live-line maintenance tasks.

5.2. Master Position Referenced (Virtual Fixture) Scheme: Unilateral Control

5.2.1. Coordinate mapping

This set of experiment aims at observing how well the concept of virtual fixtures increases the performance of slave hydraulic manipulators that are used to perform live-line maintenance tasks. The tests are performed on the Kodiak hydraulic manipulator only. Two hand-controllers are used to guide the slave hydraulic manipulator. The conventional joystick (see Figure 3.8a) as a benchmark is employed first. Due to linkage similarities between the slave manipulator and the joystick, the angular displacements of joystick are directly mapped to the angular displacements of the slave manipulator [109].

This mode is herewith called joint-mapping mode (JM mode). The end-effector mapping (EM) mode uses the PHANToM Desktop haptic device without force capability (see Figure 3.9). In this scheme, the position of the haptic device is scaled up, and then sent to the slave manipulator [109]. The angular displacements of the slave hydraulic manipulator are then calculated using inverse kinematic equations (see Section 3.2.2). The EM is further augmented by a virtual fixture (VF) force to increase the position accuracy at the haptic device. The coordinate mapping of VF mode is, however, similar to the EM mode.

In all schemes, the NPI controller, explained in Section 3.2.2, is used to control the joint angles of the slave manipulator. Figure 5.1 presents the block diagram of the teleoperated system working under JM mode. Since the joystick has the same kinematic geometry as the Kodiak hydraulic manipulator, the mapping of the joint displacements is straightforward. The actual angular displacement vector from the joystick ($\vec{\theta}_a^m$) is measured by encoders, and simply sent to the manipulator side as desired angular displacement vector at the slave site ($\vec{\theta}_d^s$). Hydraulic actuators are driven, and the manipulator end-effector travels along the intended path.

In the EM mode, shown in Figure 5.2, the force capability of the device is not utilized. Here, the operator moves the haptic device end-effector. The actual position of the operator's hand is continuously recorded ($\vec{P}_{i,a}^m$), and then multiplied by a mapping factor (α_s) in order to obtain the desired position of manipulator end-effector ($\vec{P}_{e,d}^s$). The desired angular displacement vector of manipulator joints ($\vec{\theta}_d^s$) is then obtained using Equations (3.12) to (3.15). Note that the desired position of hydraulic manipulator end-effector and

the actual position of haptic device end-effector are denoted by $\vec{P}_{e,d}^s = (x_{e,d}^s, y_{e,d}^s, z_{e,d}^s)$, and $\vec{P}_{i,a}^m = (x_{e,a}^m, y_{e,a}^m, z_{e,a}^m)$, respectively.

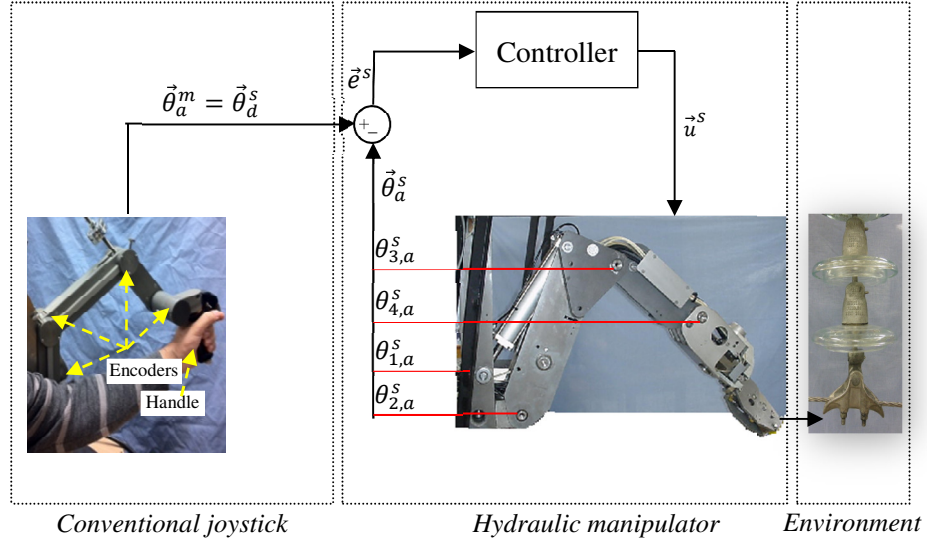


Figure 5.1 Block diagram of teleoperated hydraulic manipulator using JM mode. Joint angular displacements of joystick are the desired angular displacements of manipulator joints. Actual angular displacement of joystick joints is denoted by $\vec{\theta}_a^m = [\theta_{1,a}^m, \theta_{2,a}^m, \theta_{3,a}^m, \theta_{4,a}^m]^T$.

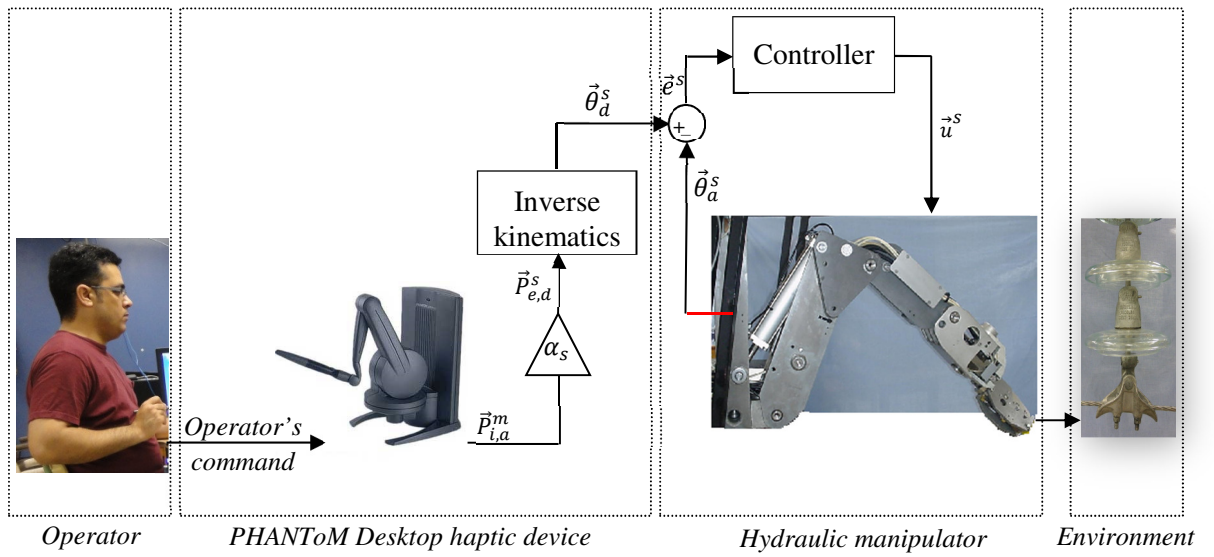


Figure 5.2 Block diagram of teleoperated control system in EM mode.

The virtual fixture (VF) scheme works similar to the EM; expect for the haptic device is programmed to produce virtual fixture force feedback which pulls the operator's hand toward the desired trajectory [82]. In this study, an impedance-type FRVF is used. When the operator moves the haptic implement towards a forbidden region, the haptic device actuators generate a virtual force in order to avoid further hand deviations. Applying the force on the operator's hand helps the user avoid unwanted collisions between the manipulator and the surrounding environment [110].

As shown in Figure 5.3a, the virtual fixture force generated by the haptic device, $\vec{F}_{VF}$, is computed based on the position error ($\vec{E}_i^m$) between the operator's hand position (point A) and the target position (point D) at the haptic device implement,

$$\vec{F}_{VF} = -G_{VF} \vec{E}_i^m \quad (5.1)$$

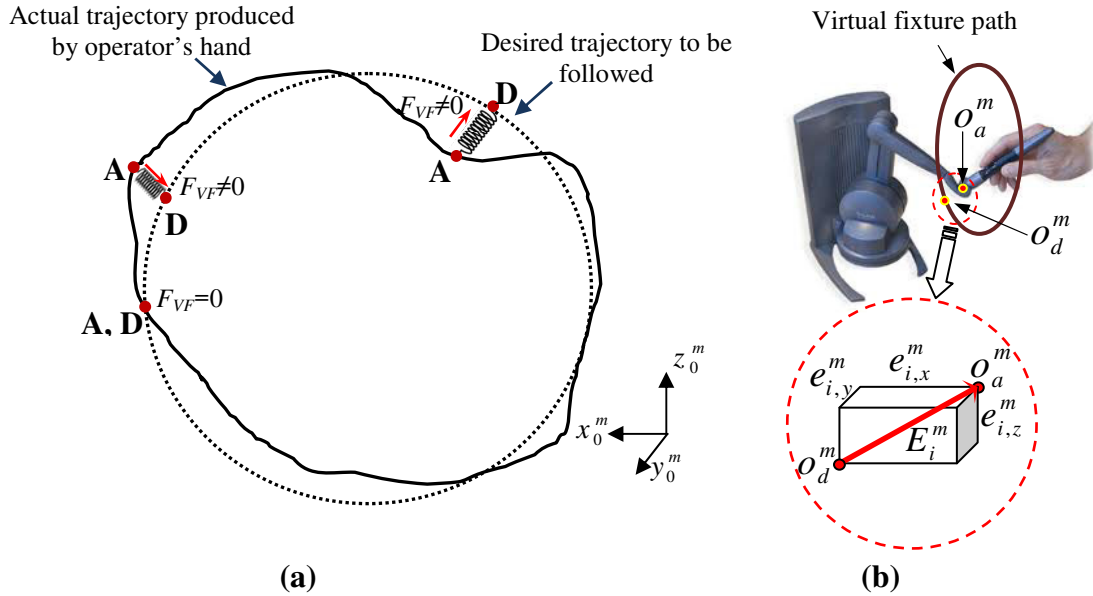


Figure 5.3 (a) Virtual spring pulls operator's hand toward desired trajectory; (b) desired (O_d^m) and actual (O_a^m) positions of haptic implement.

Referring to (5.1), G_{VF} is the stiffness matrix of the virtual spring pulling operator's hand toward the desired trajectory. With reference to Figure 5.3a, when the end-effector is on the desired trajectory, no virtual force is generated ($F_{VF} = 0$) and when the operator moves the haptic implement away from its intended trajectory, the virtual spring generates a force ($F_{VF} \neq 0$) proportional to $\vec{E}_i^m$.

As observed in Figure 5.3b, position error at the implement, denoted by $(e_{i,x}^m, e_{i,y}^m, e_{i,z}^m)$ in frame $\{x_0^m y_0^m z_0^m\}$, is expressed by three components in coordinate frame as follows:

$$\vec{E}_i^m = \begin{bmatrix} e_{i,x}^m \\ e_{i,y}^m \\ e_{i,z}^m \end{bmatrix} = \begin{bmatrix} x_{i,a}^m - x_{i,d}^m \\ y_{i,a}^m - y_{i,d}^m \\ z_{i,a}^m - z_{i,d}^m \end{bmatrix} \quad (5.2)$$

Figure 5.4 depicts the block diagram of the VF scheme in which the virtual fixture force is added to the EM scheme. Note that the force is locally provided at the master site, and no information is reflected from the slave site. Therefore, the VF scheme still works under the unilateral mode. The distance between the closest point on the desired path ($\vec{P}_{e,d}^m$), which is also called the point on the virtual fixture, and the operator's hand position ($\vec{P}_{e,a}^m$) is measured. Then, the distance ($\vec{E}_i^m$) is multiplied by the impedance of the virtual spring (G_{VF}) to calculate the haptic force. This haptic force is generated and applied to the operator's hand and pulls the hand toward the desired trajectory.

With respect to implementation, the program, written in C++, is capable of generating different paths according to each maintenance task. In the VF scheme, appropriate force vector, $\vec{F}_{VF}$, is applied on the operator's hand by the haptic device in order to keep the hand on the virtual fixture path. For example, to pull out a cotter pin (see Figure 2.2a), or insert the cotter pin back (Figure 2.2d), a line path was used as virtual fixture. To loosen and tighten a nut, a circle was defined as the virtual fixture as shown in Figure 2.2b. For

connecting and disconnecting a ball-socket joint (Figure 2.2c), a virtual fixture, combination of four straight lines, was defined. To define a virtual fixture path, first, the operator chooses the type of path such as a circle or a line. Then, based on the chosen geometry, the program allows the operator to select some points to form the virtual fixture trajectory. For instance, the circular trajectory is generated by defining its center and a point located on perimeter of the circle. The operator moves the end-effector toward the target (nut). Afterwards, the end-effector is located on the nut, and the stylus of the haptic device is pressed to determine the center coordinates. Then, the wrench is engaged with the nut, the stylus is pressed again, and the second point is defined. Now, the virtual fixture is generated, and the operator is guided to move on the defined circular path. By defining the virtual fixture, the program computes continuously the shortest distance ($\vec{E}_i^m$) between the virtual fixture (desired haptic position) and the operator's hand coordinates (actual position).

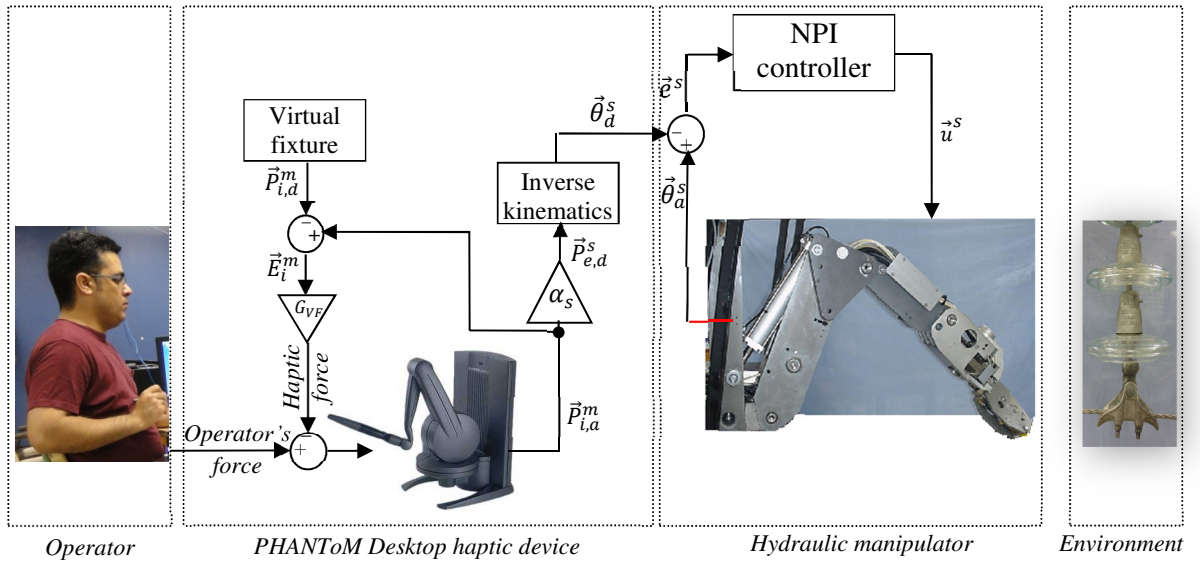


Figure 5.4. Block diagram of hydraulic telemanipulator using VF scheme. With reference to Figure 5.3b, desired haptic end-effector is denoted by $\vec{P}_{i,d}^m = (x_{e,d}^m, y_{e,d}^m, z_{e,d}^m)$.

5.2.2. Implementation and results

There were six experienced linemen from Manitoba Hydro who participated in this study. They were all right-handed and reported a normal to corrected-to-normal vision. All linemen had no experience of working with hand-controllers used in this study. All participants were trained to work with hand-controllers, concept of virtual fixture, haptics, and operation of the system. They were asked to try experiments in the simulation mode when the manipulator was switched off. They then practiced with the real system, and went through experiments to record data. The training phase was finished when the operator felt confident to use the system. The training time took an average of 15 minutes for each lineman.

A total number of $3(\text{modes}) \times 4(\text{tasks}) \times 5(\text{trials}) \times 6(\text{participants}) = 360$ trials were collected. In the JM scheme, the operators held the handle of joystick, and tried to move it to complete given tasks. In EM and VF schemes, the participants were asked to hold the stylus of the haptic device like holding a pen, and follow the given paths. The paths were defined according to real tasks usually performed by linemen (see Figure 2.2). In tests under the VF scheme, the stiffness of the virtual spring (G_{VF}) was set to:

$$G_{VF} = \begin{bmatrix} 1500N/m & 0 & 0 \\ 0 & 1500N/m & 0 \\ 0 & 0 & 1500N/m \end{bmatrix} \quad (5.3)$$

In (5.3), the amount of $1500N/m$ was tuned such that it gives feeling of an unsaturated force when $\vec{E}_i^m$ has its maximum value in practice. The effect of changing the value of (G_{VF}) was previously investigated in [110]. The quantitative evaluation was conducted by measuring three indices: (i) the task completion time which is the time taken to complete a specific task, (ii) the controller effort which is defined as integral of hydraulic value

control signal over time, and (iii) the amount of the manipulator end-effector movement. The qualitative evaluation was simply investigated, to better understand the feasibility of the system, based on the operators' opinions who tried the system experimentally in the laboratory setting. A set of eight questions, shown in Appendix, was answered by the linemen.

Figure 5.5 illustrates typical trajectories of manipulator end-effector (point E in Figure 2.2b) for all four tasks (Figure 2.2a to Figure 2.2d) and under the three JM, EM, and VF modes. Indeed, the figure shows how accurate the operator could follow the given paths. By comparing the paths depicted in each row, it is seen that the operator's hand oscillation, in the JM mode, is larger than EM and VF. For instance, Figure 5.5d shows that the operator could not follow the given circular trajectory using the JM mode. Likewise, the manipulator end-effector, in Figure 5.5a, Figure 5.5g and Figure 5.5j, was not properly guided along desired multiple-line paths, which increased the task completion time and the distance travelled by the end-effector. Also, the end-effector motion in the VF scheme is smoother than JM and EM modes, which in turn decreased the total operator's effort.

In order to quantitatively evaluate the effectiveness of the hydraulic telemanipulator, a comparative study was carried out when the system operated under JM, EM, and VF modes. Figure 5.6 depicts the mean value of each index. As seen from Figure 5.6a, the task completion time index, in JM mode, was more than the ones in EM and VF modes. For instance, during pulling out a cotter pin, the completion time for JM, EM, and VF modes were 54.02 s, 39.89 s, and 22.61 s, respectively. Furthermore, the VF scheme had

less control effort than other schemes (see Figure 5.6b), and the end-effector travelled the shortest path in the VF scheme as compared to JM and VF modes (Figure 5.6c).

With reference to Figure 5.6a and Figure 5.6c, the end-effector average velocity, in the VF scheme, was less than other modes. Therefore, the manipulator end-effector moved smoother using the VF scheme than JM and EM. In conclusion, the VF scheme was found to be the best control scheme in terms of defined indices. However, even if the VF scheme is suitable for the live-line maintenance application, we need to further ensure that results are repeatable, *i.e.*, the same behavior will be observed in future tests.

The Gaussian (normal) distribution was used to determine the validity of tests performed under the VF scheme. Two sets of normality analyses were investigated under two random variables: task completion time and position error of hydraulic manipulator end-effector. The position error was defined as the difference between the desired (coming from the master site) and actual positions of manipulator end-effector.

Table 5.1 provides the values of kurtosis and skewness of the task completion times and position errors. Kurtosis is the measure of the "peakedness" of the probability distribution of a real-valued random variable [111]. Skewness is the measure of the asymmetry of the probability distribution of a real-valued random variable [111]. A distribution is symmetric if it looks the same to the left and right of the center point. The kurtosis or skewness absolute values of more than 2 indicate that data groups differ or skew to a significant degree [112, 113]. For the VF scheme, the values of skewness and kurtosis confirm that the derived data satisfy the normal distributions criteria for all four tasks. In other words, the normality criteria are satisfied for all tasks performed using the VF scheme. Therefore, the method of experiment, using the manipulator with augmented

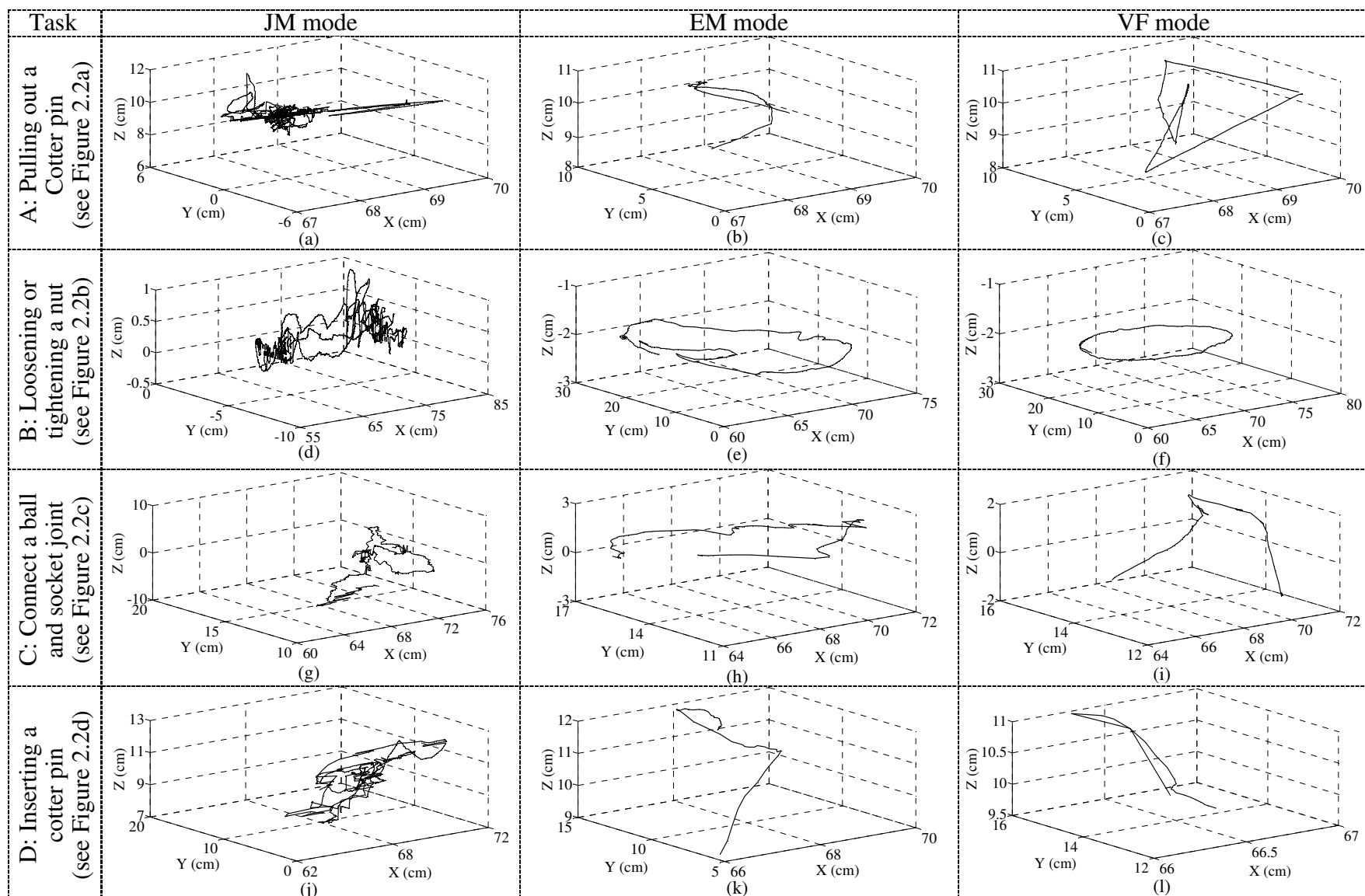
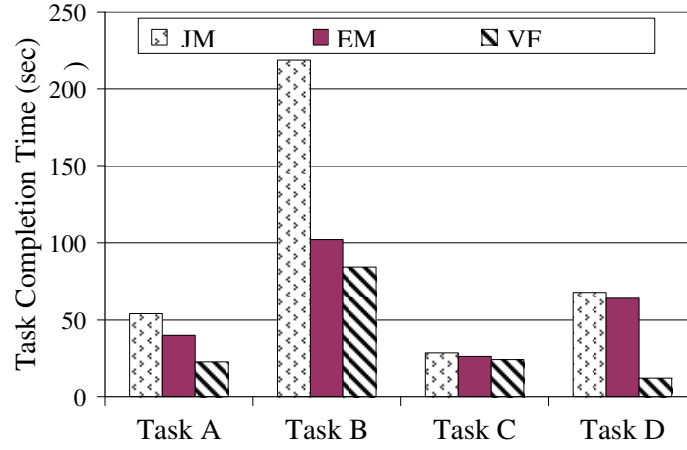
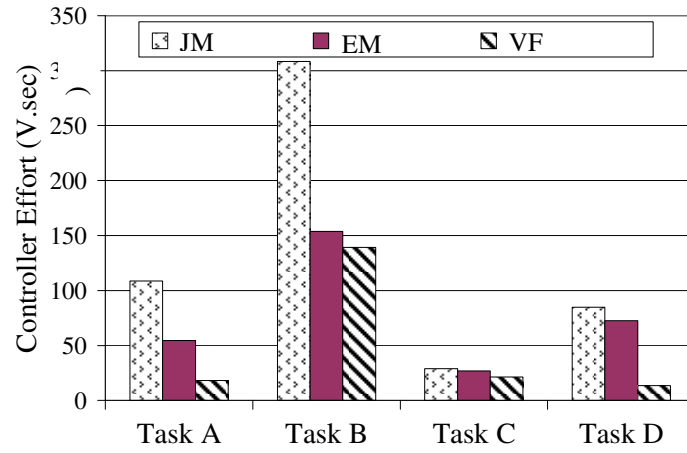


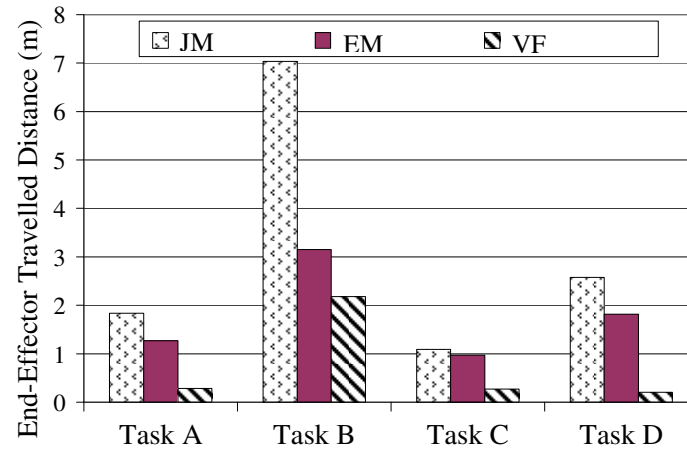
Figure 5.5 Typical test trajectories of hydraulic manipulator end-effector under JM, EM and VF modes.



(a)



(b)



(c)

Figure 5.6 Mean values of indices under JM, EM, and VF modes: **(a)** task completion time index; **(b)** controller effort index; **(c)** total distance travelled by manipulator end-effector index.

haptic device, statistically performed well according to the time measured from, and the position errors.

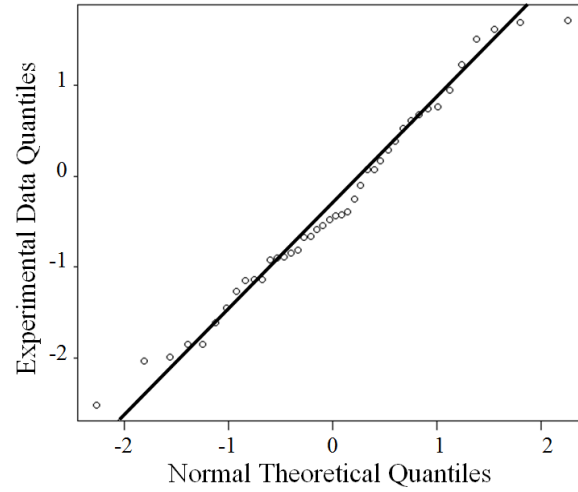
As observed in Table 5.1, skewness and kurtosis values of position errors, in Task D, are closer to 2 as compared to other tasks, which results in having less task repetition probability. The reason is that, in this task, the operator had to move the hammer fast to apply appropriate force for inserting the cotter pin (see Figure 2.2d). Therefore, the slave end-effector could not follow the master motion, and position error, at points near the pin, increased. Thus, the position error for this task is more scattered over the time as compared to the other tasks, which in turn causes in higher values for skewness and kurtosis.

Table 5.1 Statistical indices for typical tasks based on task completion time (TT) and position error of manipulator end-effector (PE) using VF scheme.

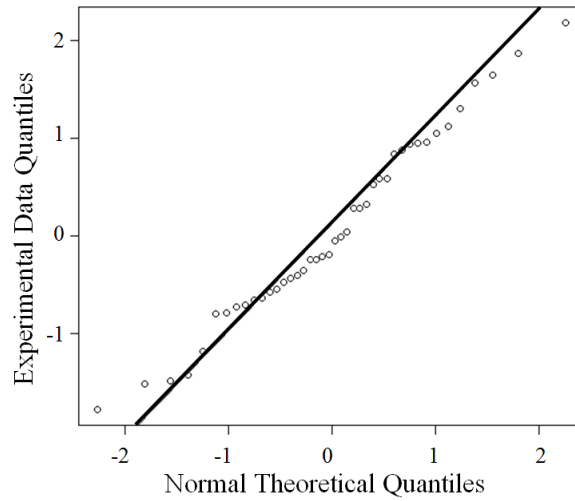
Task	Random variable		Kurtosis	Skewness
A: Pulling out a cotter pin	TT (s)	22.61	-0.251	0.959
	PE (mm)	26.40	0.750	0.849
B: Loosening and tightening a nut	TT (s)	84.23	-0.412	-0.261
	PE (mm)	12.10	1.07	1.306
C: Connecting or disconnecting a joint	TT (s)	12.07	0.090	1.144
	PE (mm)	30.65	1.387	1.406
D: Inserting a cotter pin	TT (s)	24.10	0.554	1.106
	PE (mm)	46.50	1.974	1.518

The second method to recognize the type of distribution, or more specifically to investigate the normality of a group of data, is to use the Q-Q plot which provides graphical information about statistical properties such as mean and median values of random variable [114]. The R studio software was used to plot the Q-Q diagrams. The plots indicate that for all four tasks, the points follow a linear pattern. This pattern suggests that the data are distributed as a standard normal. Thus, the robot is guaranteed

to perform well for defined tasks under the VF scheme. Figure 5.7 depicts two typical Q-Q plots of task completion times (Figure 5.7a), and position errors of manipulator end-effector (Figure 5.7b), when the telemanipulator was used to loosen and tighten a nut (Task B).



(a)



(b)

Figure 5.7 Typical Q-Q plots of (a) task completion times, and (b) position errors, in Task B and under VF scheme.

A qualitative study was also conducted, for the VF scheme, based on the operators' opinions who examined the system in a laboratory environment. Six experienced linemen participated in this survey. The results of this study are shown in Figure 5.8. As observed, the linemen agreed that live-line maintenance task can successfully be performed by the system using cameras as indirect visual feedback. In terms of safety, there was a broad range of inconclusive opinions. The reason is that the linemen believe their current job, as a lineman, is already safe and the system does not change their feelings about the safety. Based on their opinions, the task completion time was same or more than the manual operation. The linemen stated that the concept of virtual fixtures is easy to understand and learn in practice. They found the designed virtual fixtures very helpful in performing

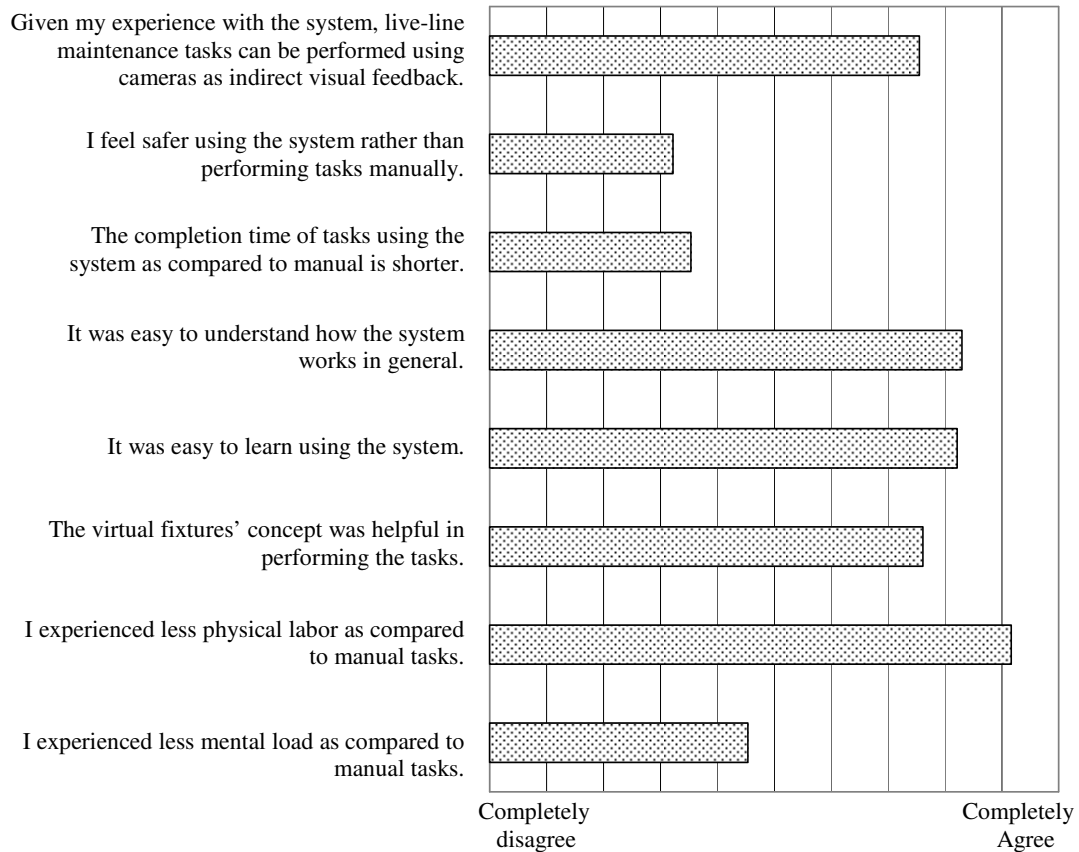


Figure 5.8 Results of qualitative study under VF scheme.

the assigned tasks. It was also confirmed that using the telemanipulator system, the physical labor was reduced up to 90% as compared to manual tasks. They believed the mental load they experienced while using the system, was similar to the manual task.

5.3. Slave Position Referenced (Force Augmentation) Scheme: Bilateral Control

The virtual fixture helped the operator keep the hand along the virtual fixture path, and corrects motion of the master device implement, which results in decreasing the position error at the slave end-effector. However, this is not adequate to ensure that position error at the slave manipulator end-effector remains small. The slave end-effector errors also originate from other sources such as speed of the operator's hand motion. Since the virtual fixture scheme provides no feedback from these sources, it cannot effectively compensate position errors at the slave end-effector. Therefore, even if the operator moves closely along the virtual fixture path, accurate position tracking of the slave manipulator cannot be guaranteed.

A set of experiments was performed that show how the operator's hand speed affects the amount of position error at the slave end-effector. The tests were conducted on the test rig shown in Figure 3.4. The operator was asked to move the haptic implement along a circular trajectory (see Figure 2.2b) with four different speeds, slow to fast, which resulted in different task completion times. The measured times were: 30.58 s, 22.50 s, 13.52 s and 8.77 s. Figure 5.9 shows position error at the haptic end-effector under different hand speeds or task completion times along the defined circular path. As observed, by increasing the hand speed, no obvious changes on the value of position error at the haptic device can be noticed, *i.e.* the ranges of position error were almost similar.

The maximum position error at the master implement was about 1.7 mm, which indicates the virtual fixture was able to keep the operator's hand very close to the desired track. However, the position error at the manipulator end-effector significantly increased, and its value was beyond the error inherently originated from the controller response.

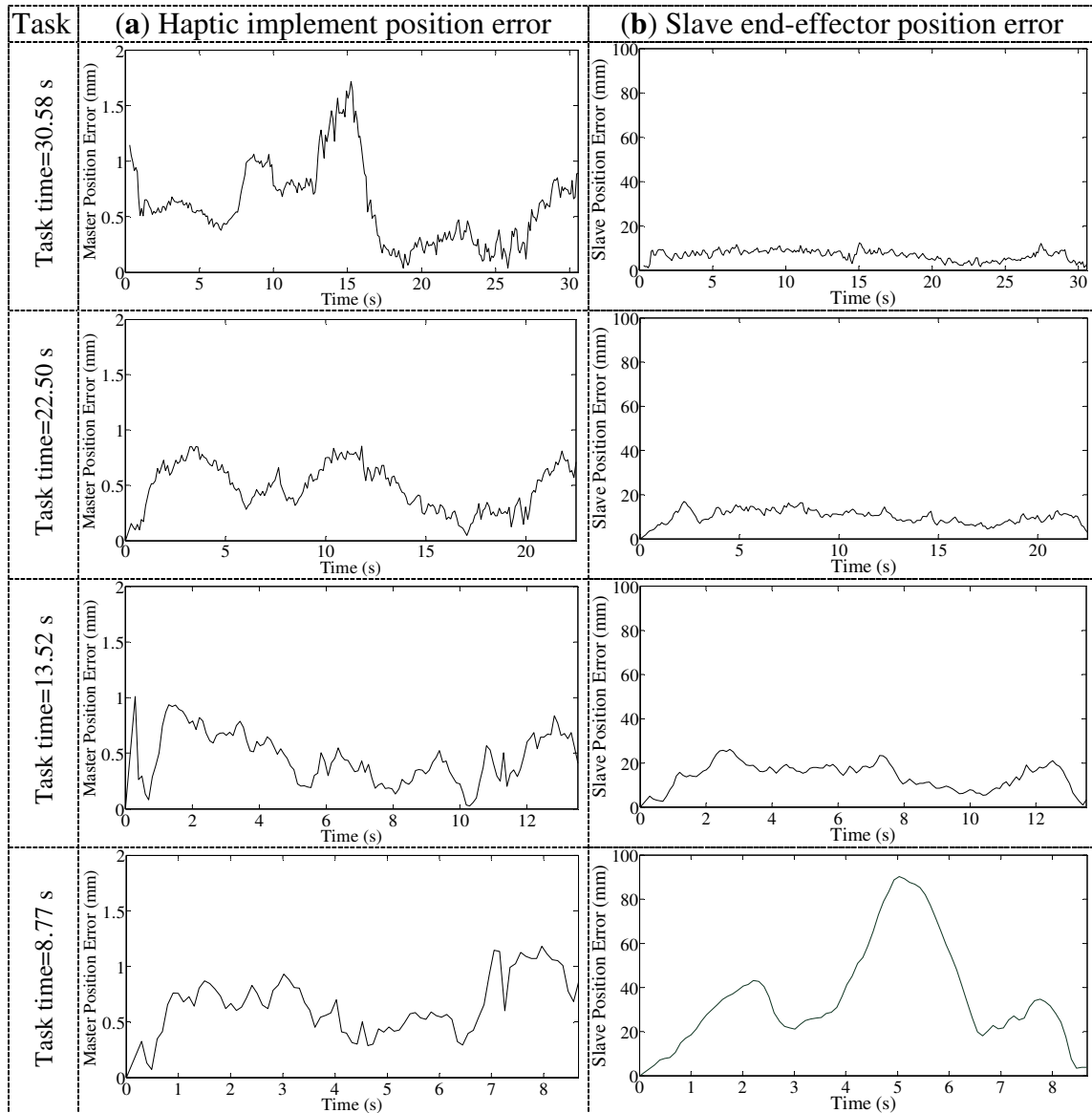


Figure 5.9 Position error at the haptic implement and manipulator end-effector, given the same task as in Figure 2.2b and under different speeds. The tests are conducted using VF scheme.

The solution to reduce position error at the slave end-effector, proposed in this section, is to add an augmentation force to the virtual fixture force. The augmentation force signals the operator to slow down the haptic implement (hand) motion when the position error becomes larger than the accuracy expected from the controller at the slave end-effector. The direction of this force should be opposite to the haptic implement (hand) instantaneous velocity. Indeed, this force allows the operator to realize position error at the slave site. The augmentation force is defined as follows:

$$\vec{F}_{AU} = \begin{cases} -|G_{AU}(\vec{E}_e^s - \vec{E}_{threshold}^s)|\hat{v}_{ins}^m & \|\vec{E}_e^s\| > \|\vec{E}_{threshold}^s\| \\ 0 & \|\vec{E}_e^s\| \leq \|\vec{E}_{threshold}^s\| \end{cases} \quad (5.4)$$

As shown in Figure 5.10, $\vec{E}_e^s$ is the vector of position error at the manipulator end-effector, and is expressed by three components in frame $\{x_0^s y_0^s z_0^s\}$. Note that due to inherent error of the controller, the augmentation force is only generated when the position error is greater than a threshold ($\vec{E}_{threshold}^s$) which is defined based on the steady-state positioning error originating from the manipulator's controller and sensors' resolution. When $\|\vec{E}_e^s\| \leq \|\vec{E}_{threshold}^s\|$, the haptic device does not produce any augmentation force. When $\|\vec{E}_e^s\| > \|\vec{E}_{threshold}^s\|$, $\vec{F}_{AU}$ is proportional to $\vec{E}_e^s - \vec{E}_{threshold}^s$ in terms of magnitude, and parallel to $\hat{v}_{ins}^m$ which is the unit vector of haptic implement instantaneous velocity. The negative sign indicates the augmentation force is in opposite direction from the haptic device instantaneous velocity. G_{AU} is a diagonal matrix. The threshold is considered to prevent repeated activation-deactivation cycles.

With reference to Figure 5.10, the position error ($\vec{E}_e^s$) that appears at the slave end-effector is defined as:

$$\vec{E}_e^s = \begin{bmatrix} e_{e,x}^s \\ e_{e,y}^s \\ e_{e,z}^s \end{bmatrix} = \begin{bmatrix} x_{e,a}^s - x_{e,d}^s \\ y_{e,a}^s - y_{e,d}^s \\ z_{e,a}^s - z_{e,d}^s \end{bmatrix} = \begin{bmatrix} x_{e,a}^s - \alpha_s x_{i,d}^m \\ y_{e,a}^s - \alpha_s y_{i,d}^m \\ z_{e,a}^s - \alpha_s z_{i,d}^m \end{bmatrix} \quad (5.5)$$

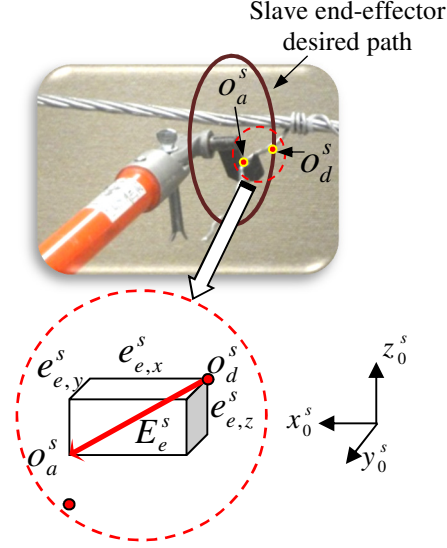


Figure 5.10 Desired (O_d^s) and actual (O_a^s) positions of slave manipulator end-effector. Position error at the end-effector is expressed by $(O_{e,x}^s, O_{e,y}^s, O_{e,z}^s)$ in coordinate frame $\{x_0^s, y_0^s, z_0^s\}$.

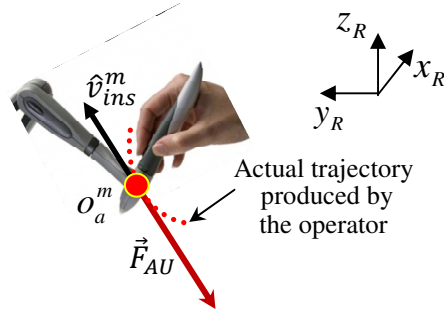


Figure 5.11 Unit vector of operator's hand velocity ($\hat{v}_{ins}^m$) and haptic augmentation force ($\vec{F}_{AU}$).

5.4. Augmented Virtual Fixture Scheme: Bilateral Control

The augmented virtual fixture is a combination of virtual fixture scheme and position referenced force augmentation. Figure 5.12 shows how the augmented virtual fixture force is calculated using the virtual fixture and the augmentation forces. As illustrated in Figure 5.12, while the virtual fixture force ($\vec{F}_{VF}$) pulls the operator's hand toward the haptic desired path, the position referenced augmentation force ($\vec{F}_{AU}$) slows down the operator's hand motion. The augmented virtual fixture force ($\vec{F}_{AVF}$) is then calculated as below:

$$\vec{F}_{AVF} = \rho_{VF}\vec{F}_{VF} + \rho_{AU}\vec{F}_{AU} \quad (5.6)$$

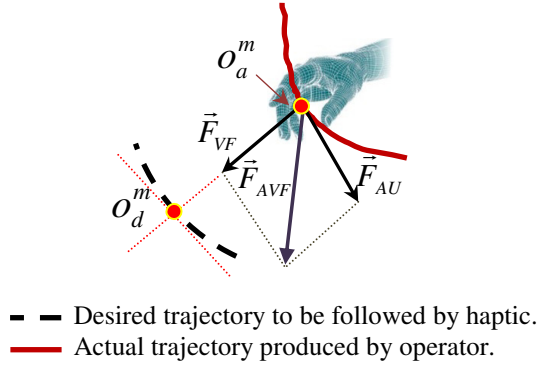


Figure 5.12 Augmented virtual fixture scheme.

where ρ_{VF} and ρ_{AU} are the weighting factors to adjust the relative effect of virtual fixture force and augmentation force, respectively. Note that $\rho_{VF} + \rho_{AU} = 1$.

The block diagram of the augmented virtual fixture scheme is illustrated in Figure 5.13. The actual position of the haptic implement ($\vec{P}_a^m$) is continuously recorded to determine position error at the haptic implement, $\vec{E}_i^m$. Next, $\vec{E}_i^m$ is multiplied by the master impedance, G_{VF} , in order to calculate the virtual fixture force ($\vec{F}_{VF}$). On the slave

site, the actual position of the haptic device is multiplied by the scaling factor, α_s , in order to calculate the desired position of the manipulator end-effector, $\vec{P}_d^s$ (see Section 5.3). The actual position of the slave manipulator end-effector, $\vec{P}_a^s$, is calculated by substituting the actual angular displacements of joints ($\vec{\theta}_a^s$) into forward kinematic equations. Having manipulator end-effector position error vector, the augmentation force, $\vec{F}_{AU}$, is calculated using Equation (5.6). The combined virtual fixture and augmentation forces form the augmented virtual fixture force.

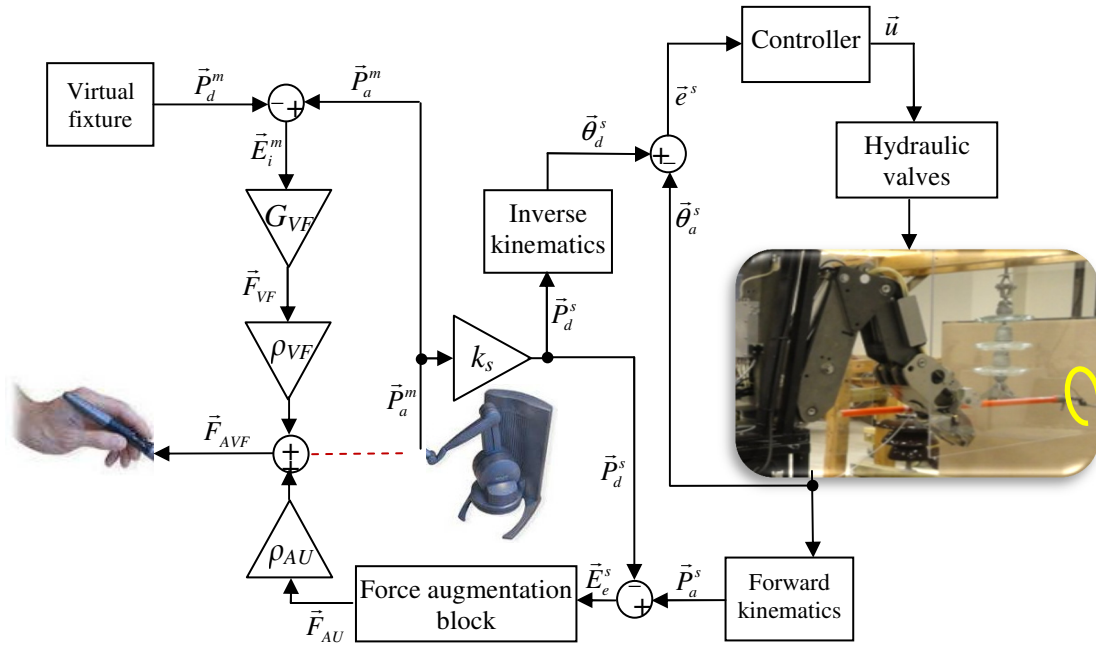


Figure 5.13 Block diagram of augmented virtual fixture scheme.

5.5. Experimental Results

Two sets of experiments are presented in which eight operators were asked to perform typical maintenance tasks (shown in Figure 2.2) with the help of a PHANToM Desktop haptic device. There were four typical tasks emulated by the experimental setup: pulling

out a cotter pin (Figure 2.2a), loosening or tightening a nut (Figure 2.2b), connecting or disconnecting a ball and socket joint (Figure 2.2c), and twisting tie wire (Figure 2.2e). Figure 2.2 illustrates trajectories (virtual fixture paths) along which the operators were asked to move the hydraulic manipulator end-effector.

The experiments were conducted using first the virtual fixture force only ($\rho_{VF} = 1$, $\rho_{AU} = 0$). Next, the augmented virtual fixture force was applied ($\rho_{VF} = 0.5$, $\rho_{AU} = 0.5$). Effectiveness of each mode was evaluated using two indices: position error at the haptic device implement and position error at the manipulator end-effector.

The operators were asked to hold stylus of the haptic device like holding a pen, and try to trace each path. The experiment was repeated 10 times by each operator, for each mode. A total number of $2(\text{force modes}) \times 4(\text{tasks}) \times 10(\text{trials}) \times 8(\text{participants}) = 640$ trials were collected. The NPI controller was employed to control each joint of the hydraulic manipulator [80]. This controller produced maximum steady-state error reflecting a threshold of 1.54 mm, 1.06 mm and 2.07 mm at the end-effector along x_0^s , y_0^s and z_0^s , respectively. Thus, the threshold is $\vec{E}_{threshold}^s = [1.54mm \ 1.06mm \ 2.07mm]^T$.

Figure 5.14 illustrates typical trajectories of slave manipulator end-effector for all four tasks and under virtual fixture as well as augmented virtual fixture schemes. This figure shows how accurately the operator could follow the given paths. As observed, there exist some deviations from the desired path in slave end-effector trajectory which result in position error. By comparing trajectories depicted in each row, it is found that the position error at the slave end-effector, in the virtual fixture scheme, is larger than the augmented virtual fixture scheme. In other words, the end-effector motion in the

augmented virtual fixture mode is more accurate than the virtual fixture scheme, which in turn is expected to decrease the total operator's effort.

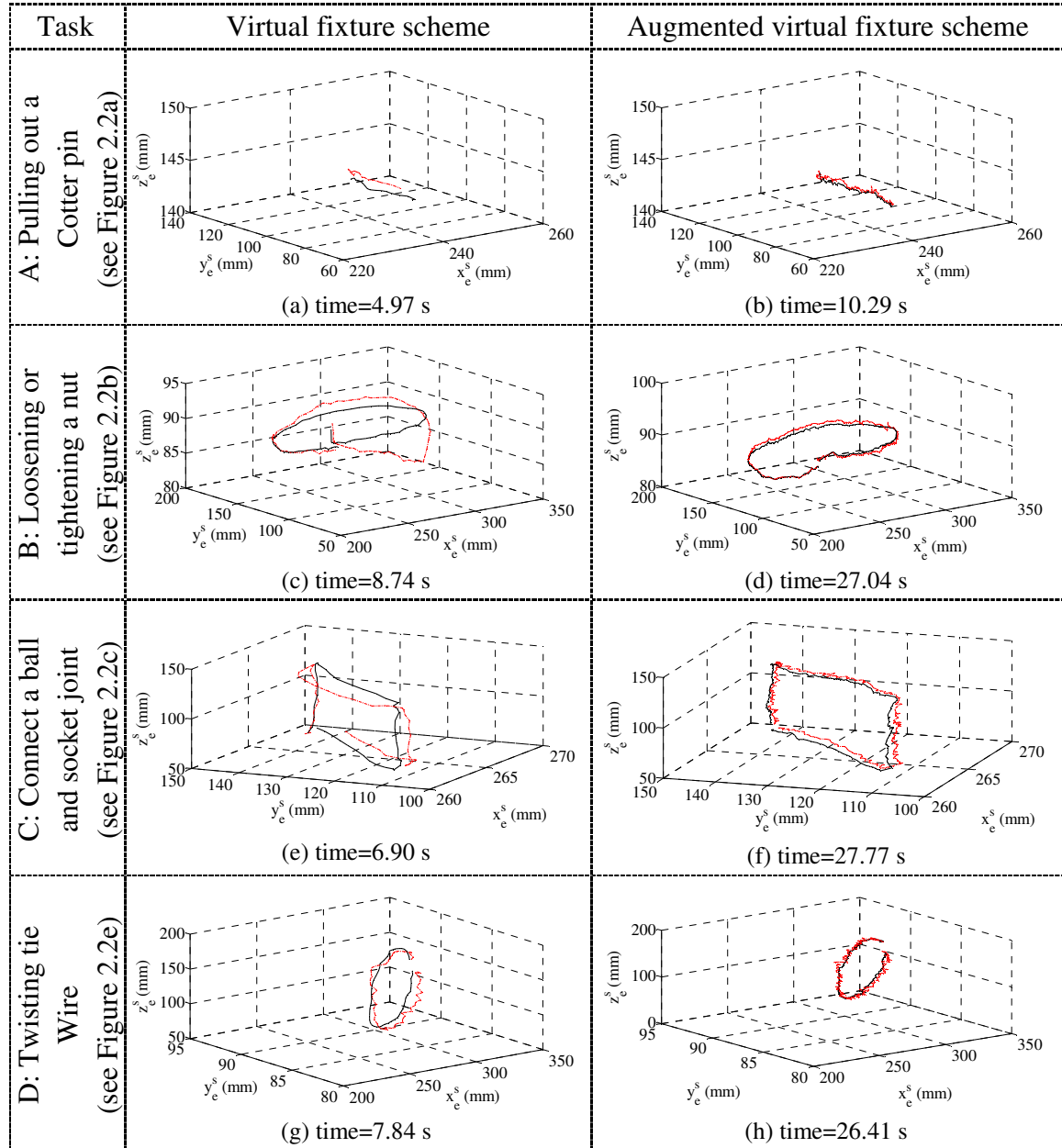


Figure 5.14 Typical test trajectories of slave hydraulic manipulator end-effector, shown in Figure 2.2, and under (a) virtual fixture mode, and (b) augmented virtual fixture mode.

For instance, Figure 5.14 c and Figure 5.14 e show that the operator could not follow the given circular and rectangular trajectories using the virtual fixture. Likewise, the manipulator end-effector, in Figure 5.14 g, was not properly guided along the desired vertical curve. The values of task completion time indicate that, in augmented virtual fixture, the operator guided the slave end-effector slower than the augmented virtual fixture mode. Note that these typical trajectories were randomly chosen from 640 trials. Therefore, the quality of slave end-effector trajectory could change from an operator to another one. However, results seen in Figure 5.14 are in line with findings in quantitative study.

Figure 5.15 depicts the mean value of position errors at the haptic device implement, over 640 trials. For each task a definite number of sampled points were defined. The actual and desired positions of the haptic device were recorded in each trial. Position errors were then calculated by averaging sampled points errors. As observed, both the virtual fixture and the augmented virtual fixture modes showed small position error at the haptic implement (less than 2.20 mm). Figure 5.16 shows the mean values of position errors at the slave end-effector, over all 640 tests. The mean errors in virtual fixture force mode are approximately three times larger than the ones from the augmented virtual fixture force mode. The mean values of radial errors at the slave end-effector were 20.80 mm in virtual fixture, and 6.02 mm in augmented virtual fixture.

Table 5.2 shows the mean values of position errors at slave end-effector for each force mode. As seen, the augmented virtual fixture has less position error at the hydraulic manipulator end-effector as compared to the virtual fixture mode. Specifically, adding the augmentation force to the virtual fixture decreased the slave position error by 71%. In

general, the augmented virtual fixture was found better in achieving small tracking position error in the tested hydraulic telemanipulator. Note that as a result of reducing position error at the slave end-effector, the task completion time naturally increases using the augmented virtual fixture. Figure 5.17 depicts the task completion times of each force mode. In all four tasks, the mean value of task completion times in augmented virtual fixture mode is higher than the task completion times in virtual fixture mode.

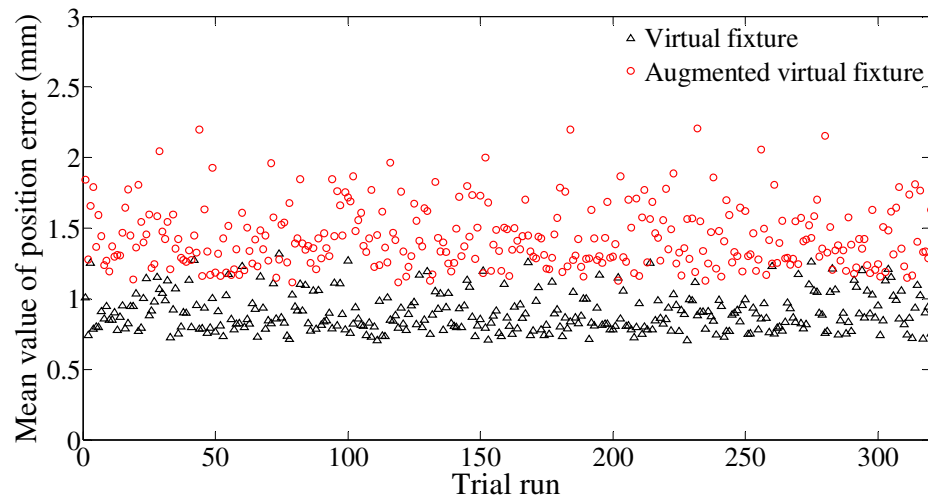


Figure 5.15 Mean values of position errors at master haptic device implement.

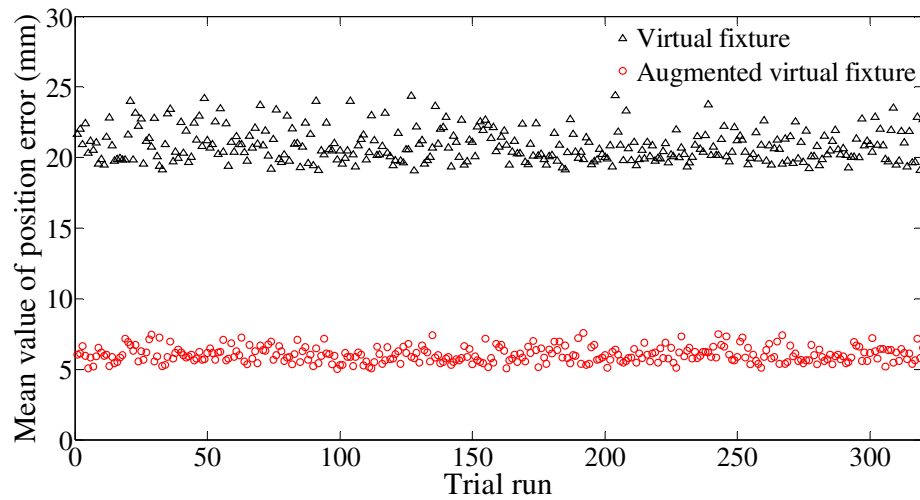


Figure 5.16 Mean values of position errors at slave manipulator end-effector.

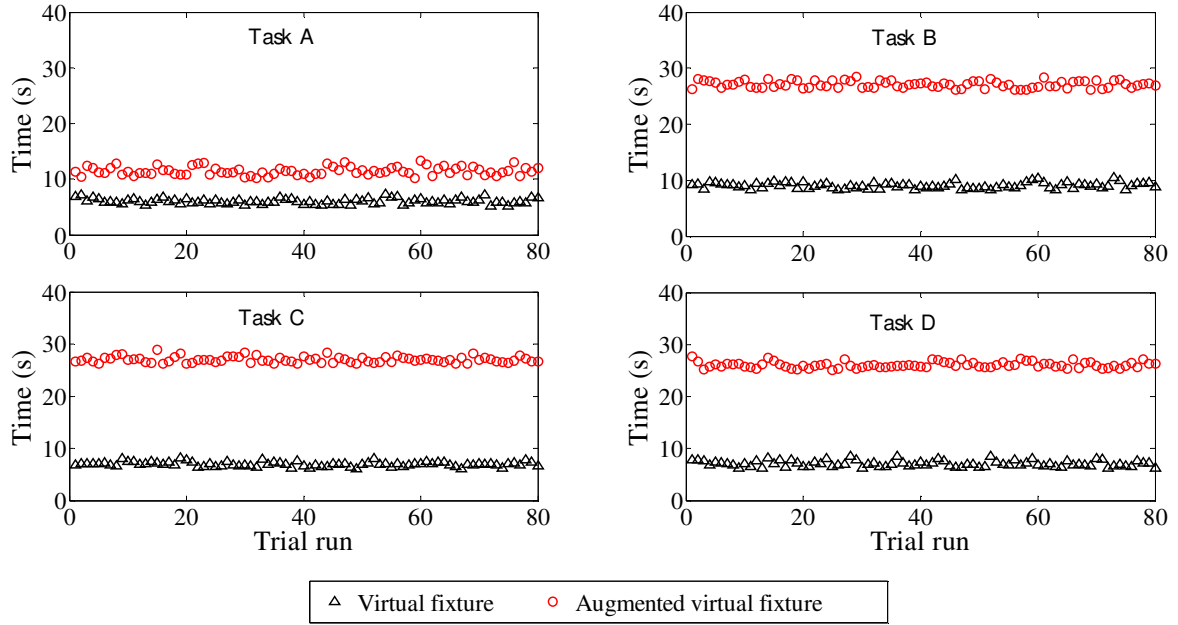


Figure 5.17 Task completion times.

As seen from Table 5.2, the kurtosis and skewness values show that both virtual fixture and augmented virtual fixture modes exhibited acceptable ranges when the random variable is position error at the slave end-effector. However, when the virtual fixture mode is tested, the absolute values of measures are closer to 2 as compared to the augmented virtual fixture. This indicates that in addition to having larger values of position error at the slave end-effector, the virtual fixture mode is less reliable than the augmented virtual fixture in reproducing similar results.

Table 5.2 Statistical measures of indices in force modes.

Force mode	Mean value	Kurtosis	Skewness
Virtual fixture	20.80	0.935	1.800
Augmented virtual fixture	6.02	-0.070	0.593

5.6. Summary

This chapter presented evaluation of the teleoperated hydraulic manipulator developed to perform live-line maintenance tasks under two unilateral and bilateral modes. In unilateral front, the performance of the teleoperated manipulator was examined by performing several live-line maintenance tasks, by six hydro linemen, under three criteria: task completion time, control effort, and total distance travelled by the manipulator end-effector. Results exhibited improved performance of the virtual fixture scheme as compared to condition at which the slave manipulator was guided by the conventional joystick or the force-disabled haptic device. Next, the position referenced force augmentation scheme was proposed to alleviate the weakness of virtual fixtures: position inaccuracy at the slave end-effector. Combined the virtual fixture with the force augmentation, the augmented virtual fixture was introduced that commands the haptic device to produce two haptic forces, which were simultaneously applied to the operator's hand. The forces were the conventional virtual fixture force and the newly-proposed augmentation force. The virtual fixture force pulls the operator's hand towards the haptic predefined (virtual fixture) path. The augmentation force, on the other hand, guides the operator to adjust the pace of their hand movement when position error is observed at the slave manipulator end-effector. Effectiveness of the scheme was evaluated by applying the concept to performing typical live-line maintenance tasks. Evaluation indices were: position error at the haptic device implement and position error at the hydraulic manipulator end-effector. Two sets of tests were performed: tests using only conventional virtual fixture force generated by the haptic device, and tests when the virtual fixture force was augmented with the force augmentation scheme. The augmented virtual fixture

was shown to be more effective than the virtual fixture, in that it simultaneously reduced position errors at both the master implement and the slave end-effector. Specifically, for performed experiments and as compared to the virtual fixture alone, the augmented virtual fixture reduced position error at the manipulator end-effector by at least 71%, and this was done by simply guiding the operator to slow down the hand motion allowing the slave manipulator to catch up with the command from the master haptic device.

CHAPTER 6

POSITION REFERENCED FORCE AUGMENTATION APPLIED TO DELAYED TELEMANIPULATORS

6.1. Introduction

Ideally, in a teleoperated hydraulic manipulator, the slave manipulator should precisely follow the master motion, *i.e.* no position error should appear at the slave end-effector. However, position error exists due to many reasons such as lack of responsiveness in controller or actuation system and coupled dynamics. Moreover, when the system operates under a delayed and/or lossy network, both slave and master sites receive the information of the other site with a delay. Therefore, the position error at the slave end-effector is considerably magnified.

One method to decrease the position error is to predict the delays and losses in the communication channel, and then apply the predicted variables to the control system [115, 116, 117, 118]. This chapter shows how the force augmentation scheme is used to alleviate the effect of delayed or lossy networks on the position error. Indeed, while the

operator cannot accurately perceive the position error, due to network delay and packet loss, the force allows her/him to stay alert of how far the hydraulic manipulator lags behind the haptic device.

6.2. Description of the Scheme

Figure 6.1 shows the block diagram of the proposed scheme. As observed, the operator moves the haptic device end-effector. Then, the actual position of the haptic implement, $\vec{P}_m^a$, is used to find the desired position of the manipulator end-effector, $\vec{P}_s^d$. The desired position is then sent to the slave site through a communication channel. The actual position of the slave manipulator end-effector, $\vec{P}_s^a$, is computed by substituting the measured angular displacements of slave joints ($\vec{\theta}_s^a$) into kinematic equations [82]. The difference between the actual and the desired positions of the slave end-effector ($\vec{P}_s^a - \vec{P}_s^d$) gives the position error at the end-effector ($\vec{E}_e^s$), which is then used to find the position referenced force ($\vec{F}_{AU}$). The magnitude of the haptic force indicates, to the operator, to move the haptic device slower, until no force is perceived. All variables, in this chapter, are in accordance with the terminologies defined in Section 5.3.

6.3. Test Procedure

Figure 6.2 illustrates the general architecture of the experimental hydraulic telemanipulator platform consisting of a master haptic device (Figure 3.8b) guided by an operator, and a slave hydraulic manipulator (see Figure 3.5). In this set of experiments, the Stewart platform is fixed, *i.e.* the manipulator is positioned on a fixed platform. As shown in Figure 6.2, three PCs (master, slave and network emulator) are connected in a

local area network (LAN) through an Ethernet hub. The intermediate computer runs the NS2 to emulate both dedicated and wireless networks.

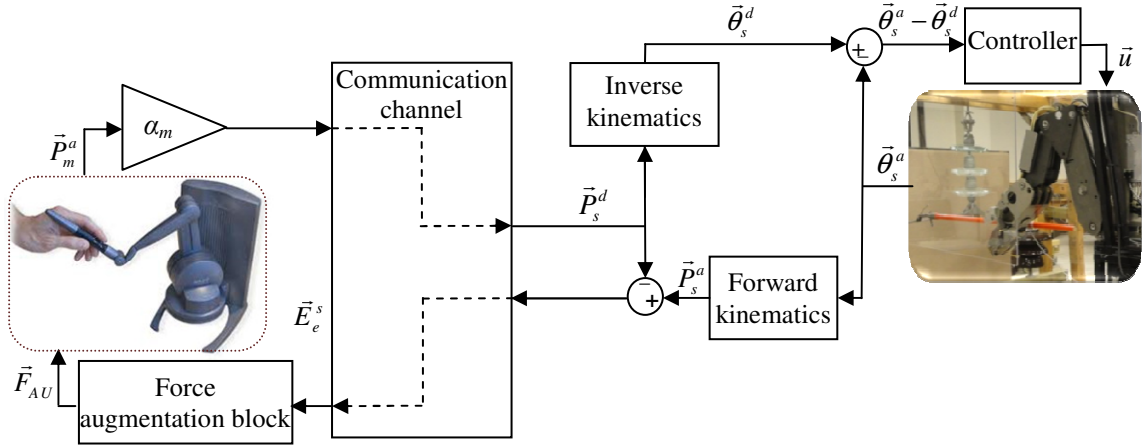


Figure 6.1 Block diagram of force augmentation scheme when teleoperated system works under a delayed/lossy network.

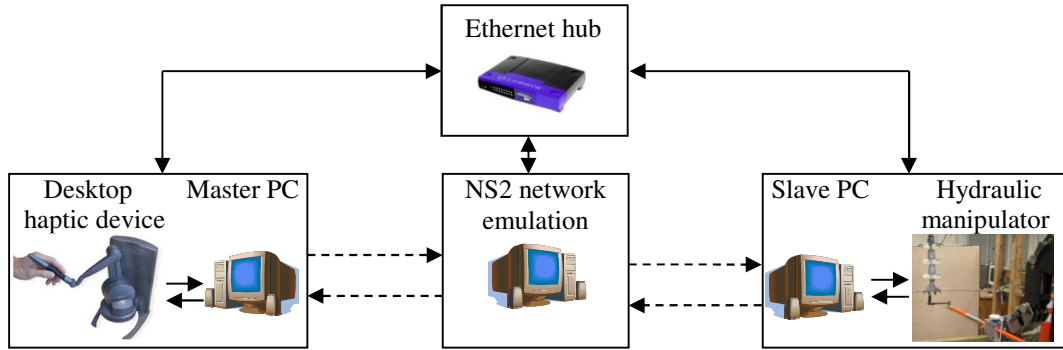


Figure 6.2 General architecture of tested telemanipulator. Solid and dashed lines show physical and logical connections, respectively.

Experiments were conducted when the force capability of the haptic device was deactivated (force-disabled mode), and then they were similarly repeated when the position referenced force was generated by the haptic device (force-enabled mode). The same operator performed all tasks. Each task was repeated 10 times. The evaluation

criterion was the position error at the slave manipulator end-effector. However, in addition to the position error, the average of the operator's hand speeds and task completion times were reported.

In the experiments, the operator was asked to move the haptic device implement along a semicircular trajectory, which resulted in guiding the hydraulic manipulator end-effector along the trajectory shown in Figure 2.2e. In total, 400 experiments were conducted involving both modes: 16 tests under dedicated network, and 4 tests under wireless communication channel. The wireless network was configured according to different combinations of obstructions in the environment and antenna transmission powers. Each test was repeated 10 times by the same operator, and performed with or without force feedback.

6.4. Results

6.4.1. Experiments using dedicated channel

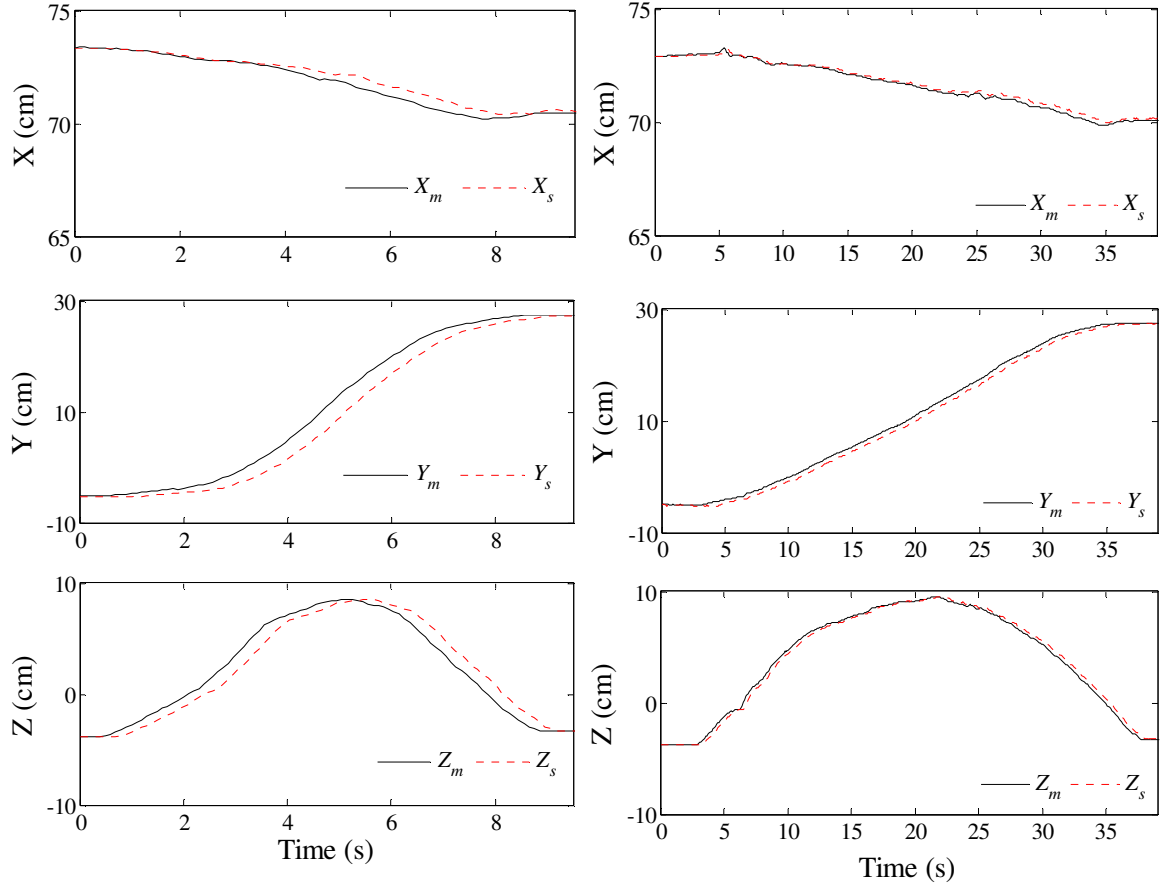
The first set of experiments was done under dedicated communication channel configured at different pairs of constant time delays and packet losses. In haptic force-enabled trials, the haptic force was generated using the position referenced force augmentation scheme. The operator was instructed to reduce the hand speed, upon sensing the haptic force, with the intention of minimizing the force. In total, 320 trial runs were conducted with and without force, each with four constant time delays (400 ms, 700 ms, 1000 ms and 1300 ms) and four constant packet losses (0%, 25%, 50% and 75%). There was an inherent 400 ms delay, originating from the processing time of the master and slave computers, included in the above time delays. The value of 400 ms was

obtained by directly connecting the master and slave PCs, without introducing any time delay in the communication channel. In all experiments, the impedance matrix (G_{AU}) was set to $diag[250N/m \ 250N/m \ 250N/m]$. Table 6.1 summarizes the test scenarios.

Table 6.1 Characteristics of dedicated networks used in first set of experiments: round-trip delay (TD) and packet loss (PL).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
TD (ms)	400				700				1000				1300			
PL (%)	0	25	50	75	0	25	50	75	0	25	50	75	0	25	50	75

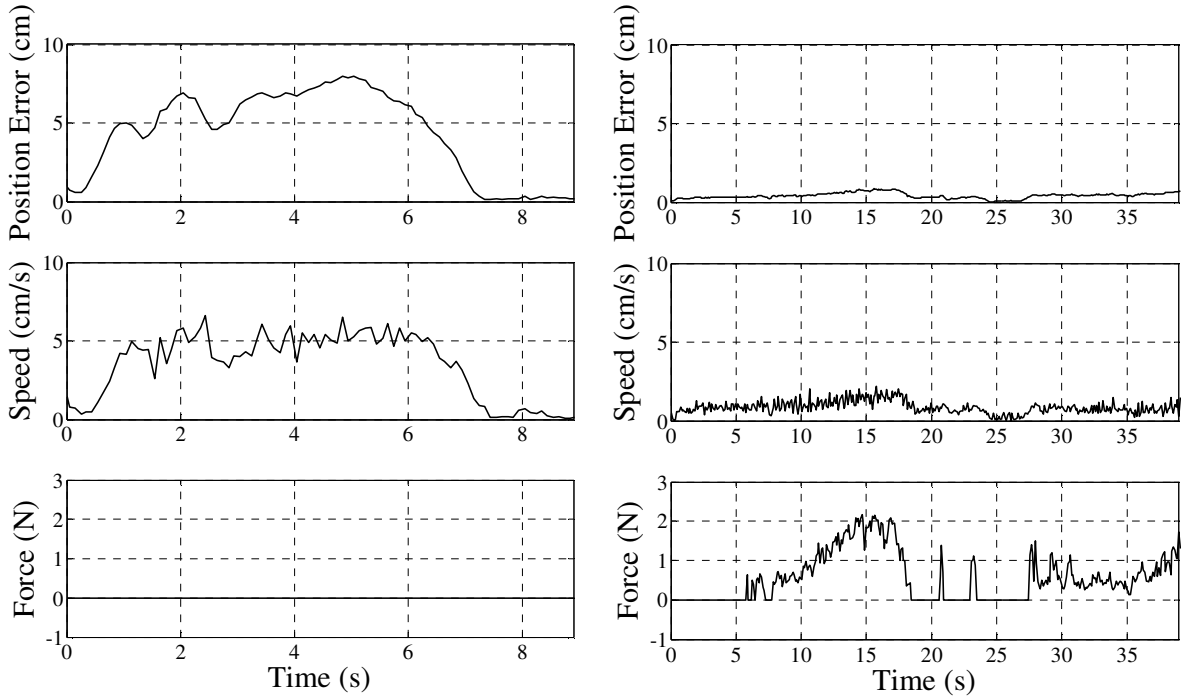
Results of two typical tests are presented: test in the presence of a significant packet loss (TD=400 ms, PL=75%) and test in the presence of a significant packet loss (TD=1300 ms, PL=0%). Figure 6.3 shows master and slave trajectories in frame $\{x_0^s y_0^s z_0^s\}$, when TD=400 ms and PL=75%. As observed, in haptic force-enabled mode, the actual position of the end-effector nearly overlaps with the commanded (desired) position as compared to the case in which no haptic force was applied. Figure 6.4 illustrates variations of the radial position error, at the slave end-effector, $\sqrt{(e_{e,x}^s)^2 + (e_{e,y}^s)^2 + (e_{e,z}^s)^2}$, the operator's hand speed, and the haptic force applied to the operator's hand. As shown in haptic force-enabled mode, incrementing the position error results in increasing the haptic force. The average position error at the slave end-effector reduced from 30.6 mm (force-disabled) to 4.2 mm (force-enabled). The average speeds in force-disabled and force-enabled tests were 4.23 cm/s and 0.92 cm/s, respectively.



Force-disabled: operator's average speed=4.23 cm/s. Force-enabled: operator's average speed =0.92 cm/s.

Figure 6.3 Typical trajectory of hydraulic manipulator end-effector in frame $\{x_0^s y_0^s z_0^s\}$, for scenario S4 (TD=400 ms and PL=75%). Subscripts 'm' and 's' indicate displacements of master and slave, respectively.

Typical position of the slave end-effector, when time delay is significant (TD=1300 ms and PL=0%) is shown in Figure 6.5. By comparing position signals of both modes, position error at the manipulator end-effector is observed to reduce when the force augmentation scheme was included in the teleoperated system. In both scenarios, reduction of the hand's speed resulted in increasing the task completion which was expected.



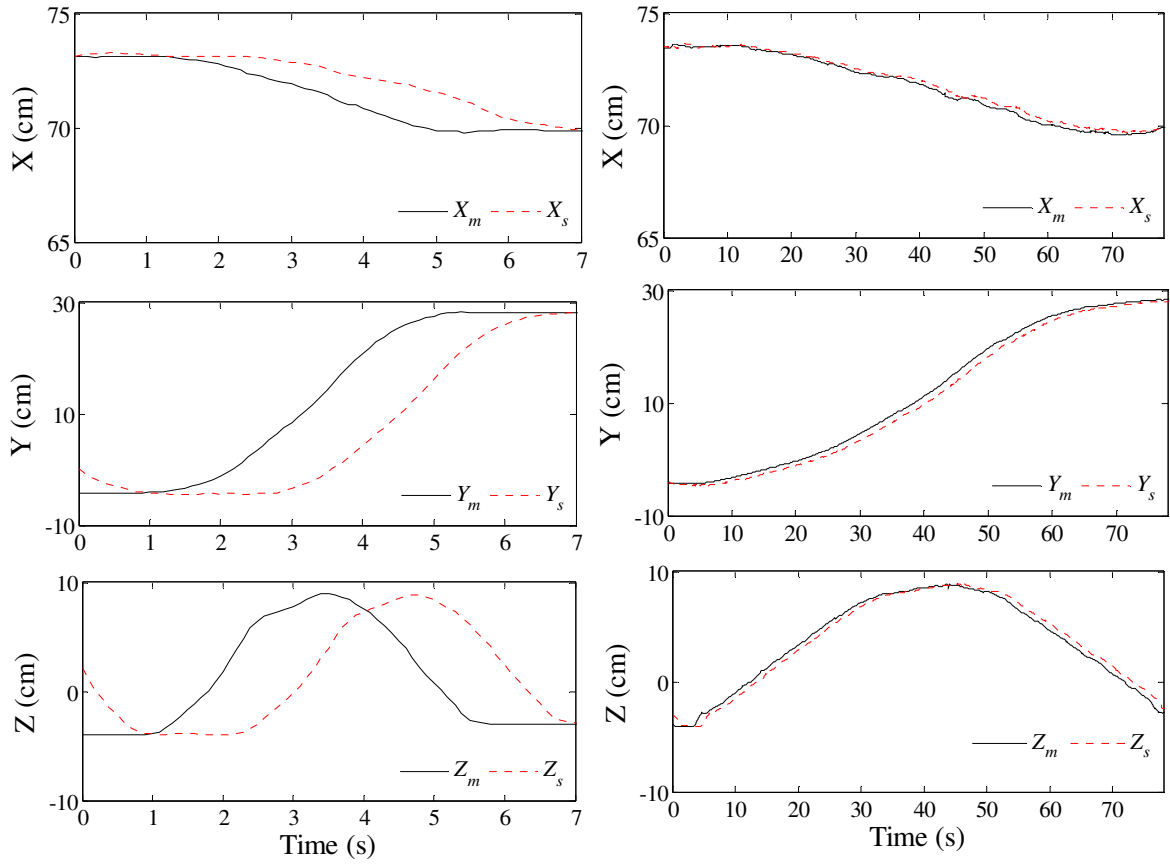
Force-disabled: average position error =3.06 cm and operator's average speed=4.23 cm/s.

Force-enabled: average position error =0.42 cm and operator's average speed =0.92 cm/s.

Figure 6.4 Position error at the slave end-effector, operator's hand speed and haptic force, for test shown in Figure 6.3.

6.4.2. Experiments using wireless channel

The effectiveness of the proposed scheme was then evaluated in the presence of wireless channel emulated by the NS2 simulator. Different antenna transmission powers, in obstructed or unobstructed environment, were emulated. Table 6.2 lists the parameters used to define test scenarios. In these tests, the wireless router was assumed to operate at 2.4 GHz with channel bandwidth of 11 Mbps. The antenna transmission power was set to 15 dBm (S17 and S19 in Table 6.1) and 18 dBm (S18 and S20 in Table 6.1) for low power and high power antennas, respectively. The receiver sensitivity was set to a common value of -83 dBm. The path loss exponent, n , was set to 2 dB (S19 and S20 in Table 6.1) and 3.5 dB (S17 and S18 in Table 6.1) to reflect unobstructed and obstructed



Force-disabled: Average speed=4.79 cm/s.

Force-enabled: Average speed=0.46 cm/s.

Figure 6.5 Trajectory of slave end-effector in frame $\{x_0^s y_0^s z_0^s\}$, for test S13 (TD=1300 ms; PL=0%).

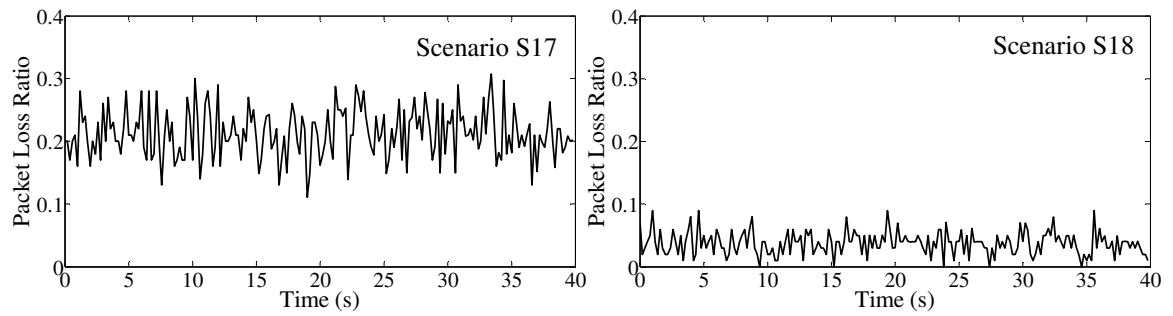


Figure 6.6 Packet losses generated in scenarios S17 and S18.

scenarios, respectively. Typical variations of packet loss and time delay over time, for scenarios S17 and S18, are shown in Figure 6.6. As expected, the packet loss randomly changes when master and slave sites are connected wirelessly. Moreover, the packet loss for scenario S18 with high power is less than the one with lower power (S17). Note that the packet loss was the dominant parameter in this set of experiments.

Table 6.2 Parameters used to emulate wireless channel using NS2 under wireless channel.

Parameter	Value
Path loss exponent	2 <i>dB</i> (unobstructed) 3.5 <i>dB</i> (obstructed)
Shadowing deviation	4.0 <i>dB</i>
Reference distance	1 <i>m</i>
Transmitting antenna gain	2 <i>dBi</i>
Receiving antenna gain	2 <i>dBi</i>
Antenna transmission power	15 <i>dBm</i> (low power) 18 <i>dBm</i> (high power)
Channel bandwidth	11 <i>Mbit/s</i>
Contention window size	1-31
Short retry limit	2
long retry limit	1
Packet size	50 <i>bits</i>
Packet interval	2 <i>ms</i>

Figure 6.7 shows position tracking of the slave manipulator end-effector when the system operated in obstructed environment and a router with the antenna power of 15 dBm was used (scenario S17). When the force was activated, the operator moved the haptic device approximately four times slower than the case when it was deactivated. Figure 6.8 depicts similar results when the environment was obstructed, and a high power antenna (18 dBm) was employed (scenario S18). From Figure 6.7 and Figure 6.8, it is observed that the position error at the end- effector decreased when the scheme was implemented in the

system. More specifically, the average position error, for scenario S18, changed from 34.2 mm to 5.27 mm when the force slowed down the operator's hand motion. It was therefore concluded that regardless of the router type and obstruction in the environment, the slave manipulator positioning was improved when the haptic device utilized the proposed force to slow down the hand's motion.

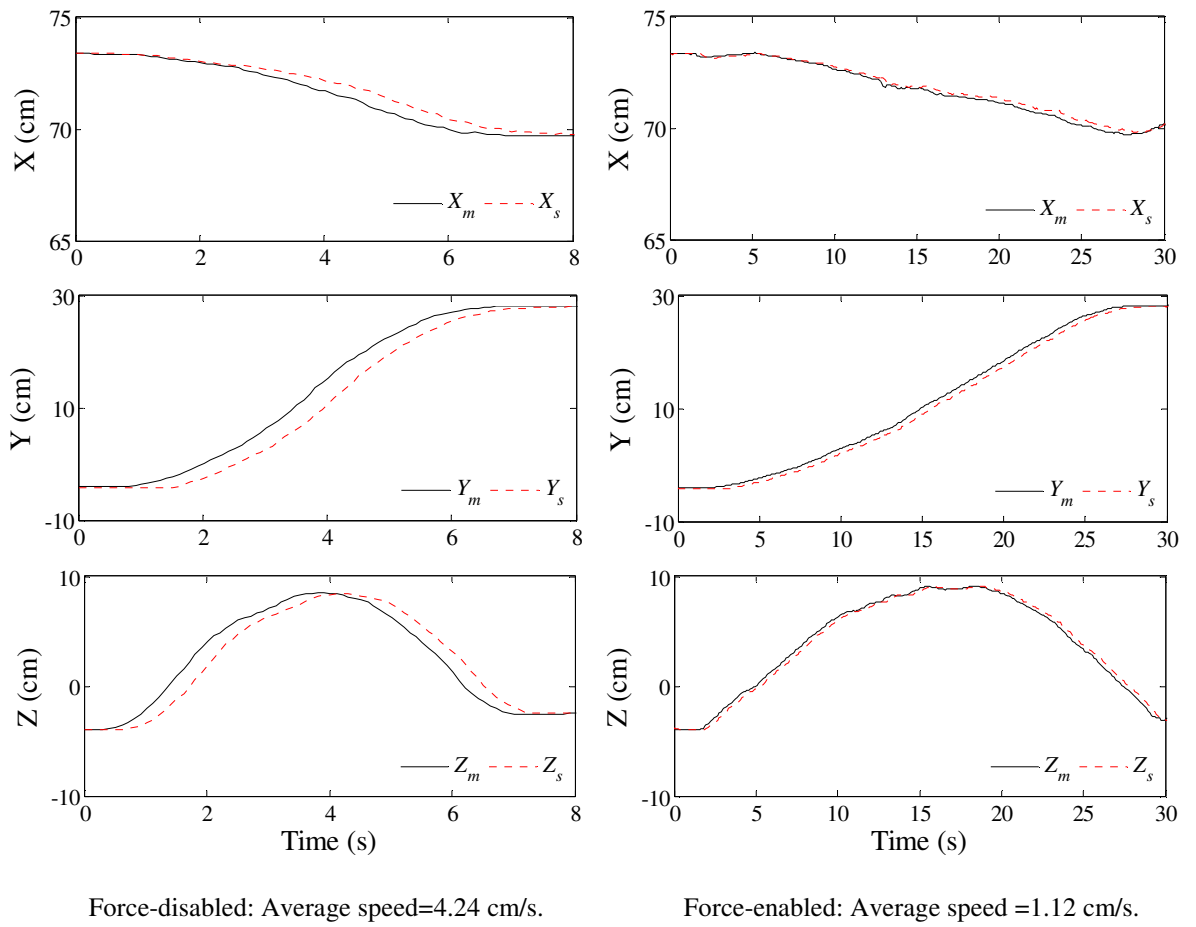


Figure 6.7 Typical trajectory of slave end-effector in frame $\{x_0^s y_0^s z_0^s\}$, for scenario S17.

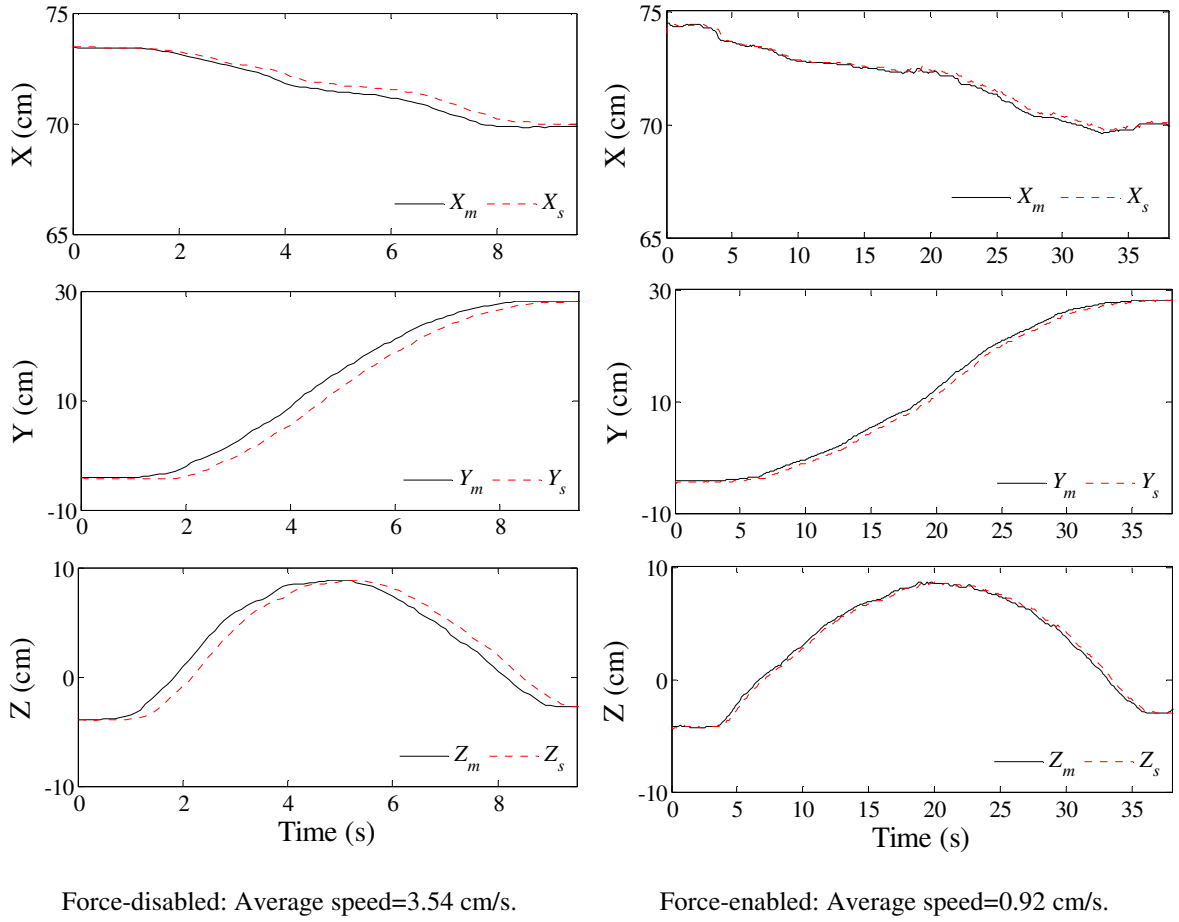


Figure 6.8 Typical trajectory of manipulator end-effector in frame $\{x_0^s y_0^s z_0^s\}$, for scenario S18.

Figure 6.9 summarizes the information collected from all 400 trial runs: mean values of position errors, task completion times, and operator's hand speeds for all 20 scenarios. Each scenario was repeated for 10 times. The mean values were calculated by averaging the corresponding values that were measured each over 10 trials. As seen, in all 20 scenarios, the mean value of position error was significantly reduced when the haptic force was enabled. More specifically, the scheme reduced position error at the slave end-effector by at least 92%. This was done by simply slowing down the haptic motion guided by the force applied to the operator's hand. As a result, the task completion time

increased four times when the scheme was included in the control. Figure 6.9 also shows the mean values of the operator's hand speed which shows how the scheme reduces the hand's speed.

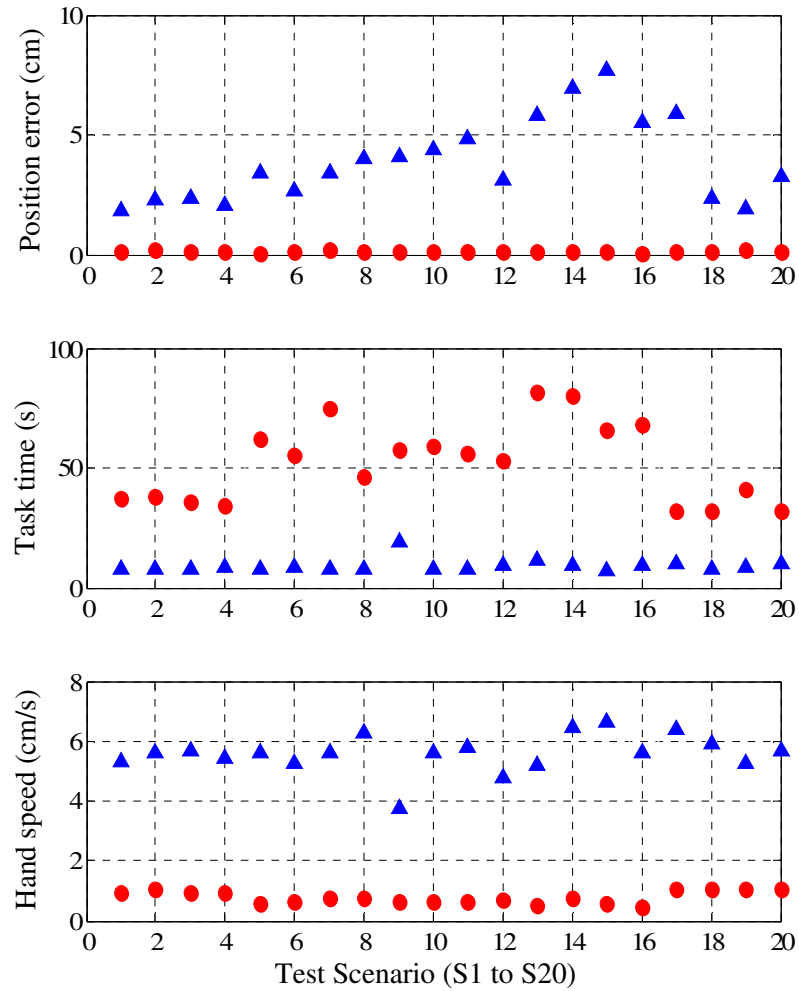


Figure 6.9 Mean values of position errors, task completion times, and operator's hand speeds without force (▲) and with force (●), for all 20 scenarios.

6.5. Summary

This chapter investigated how to use a position referenced force augmentation scheme to decrease position error, at slave end-effector in teleoperated hydraulic manipulators,

due to the presence of time delay and packet loss in a network. This scheme commands the haptic device to apply a force against the operator's hand intended motion to slow down when position error is observed at the manipulator end-effector. Effectiveness of the scheme was evaluated by conducting extensive experiments on a teleoperated hydraulic manipulator. Various scenarios of dedicated and wireless communication channels were examined. Results indicated that the force augmentation scheme could reduce the position error at the slave hydraulic manipulator up to 92% as compared to the conventional control without force. Naturally, the task completion time increased when the haptic force guided the operator to reduce the hand's speed.

CHAPTER 7

WIRELESS CONTROL OF BASE-EXCITED TELEMANIPULATORS

7.1. Introduction

In the application of live-live maintenance, three main issues were outlined in Chapter 2. They were: *(i)* design and implementation of force feedback control systems to help operators work more effectively, *(ii)* compensating for the effect of wireless network on performance of the system, and *(iii)* investigating the effect of the slave manipulator base excitation that, in practice, originates from the crane bucket motion. In this chapter, performance of the teleoperated manipulator, installed on top of a motion platform (see Figure 3.4), is experimentally evaluated under various test scenarios. Each scenario is characterized by a wireless network and a haptic force. Two indices are used to measure the performance of the system: number of operators' unsuccessful attempts, and displacement of the manipulator end-effector. Moreover, the task completion times for all experiments are reported.

7.2. Design of Experiments

7.2.1. Network setup

The wireless channel is generated by the NS2 software. Two wireless network scenarios were considered for two values of path loss exponents: free space ($n=2.0$) and free space with some obstructions ($n=3.0$). In both scenarios, specification of a Cisco Aironet 2.4-GHz MIMO Omnidirectional Antenna (AIR-ANT2440NV-R) was emulated using the NS2. The transmitter antenna worked under 2.4 MHz. The antenna transmission power was 18 dBm and the receiver sensitivity was set to -83 dBm. In all experiments, the distance between the slave and master sites, d , was 100 m. Table 7.1 lists the network setting used by NS2 in the experiments. Typical packet losses over time, for both scenarios, are illustrated in Figure 7.1.

Table 7.1 Parameters used to emulate wireless channel [119].

Parameter	Value
Path loss exponent	2.0 <i>dB</i> and 3.0 <i>dB</i>
Shadowing deviation	4.0 <i>dB</i>
Reference distance	1 <i>m</i>
Transmitting antenna gain	1 <i>dBi</i>
Receiving antenna gain	1 <i>dBi</i>
Antenna transmission power	15 <i>dBm</i>
Channel bandwidth	11 <i>Mbit/s</i>
Contention window size	1-31
Short retry limit	2
long retry limit	1
Packet size	50 <i>bits</i>
Packet interval	2 <i>ms</i>

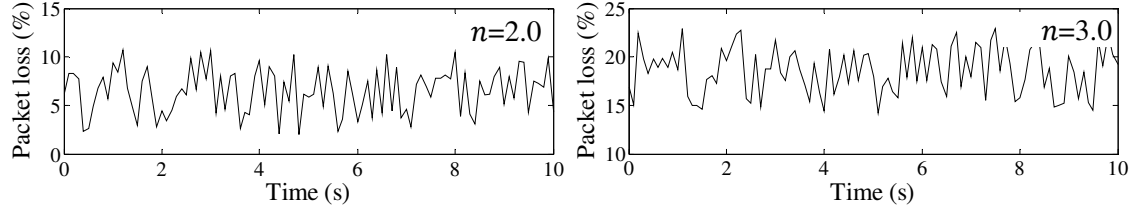


Figure 7.1 Typical packet loss for unobstructed ($n=2.0$) and obstructed ($n=3.0$) scenarios.

7.2.2. Base motion

Results of the field study, shown in Figure 4.15, showed that the crane bucket was disturbed due to unwanted phenomena such as unstable soil, wind conditions, changes in bucket load, reaction forces, and compliance in the crane actuation system. Observations also showed that there was a displacement with amplitude of 50 mm, and frequency of 0.12 Hz, that were determined by analyzing movies made during the bucket movement. Therefore, for designed experiments, the platform was programmed to generate random displacement (D_x, D_y, D_z). As seen in Figure 7.2, the displacement of the platform top plate has maximum amplitude and frequency of 90 mm and 0.24 Hz, respectively. The accurate models of the above phenomena can be studied to make the platform motion close to the reality.

When displacement of the top plate is established, the displacement of each of the hydraulic actuators ($L_{i=1..6}$) is determined by solving the inverse kinematic equation given in Equation (3.22). Figure 7.3 illustrates the actuator displacements of the Stewart platform. Note that during the operation, the operator did not know the amplitude or the frequency of the base motion; therefore, the motion was completely unseen.

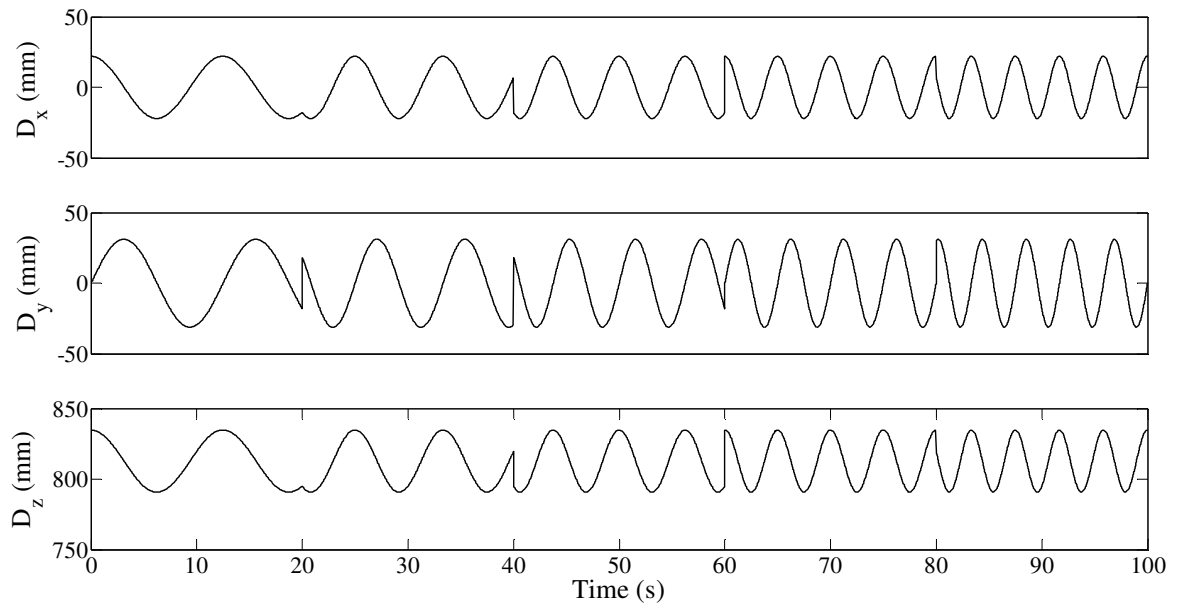


Figure 7.2 Displacement of platform top plate over a 100-second period.

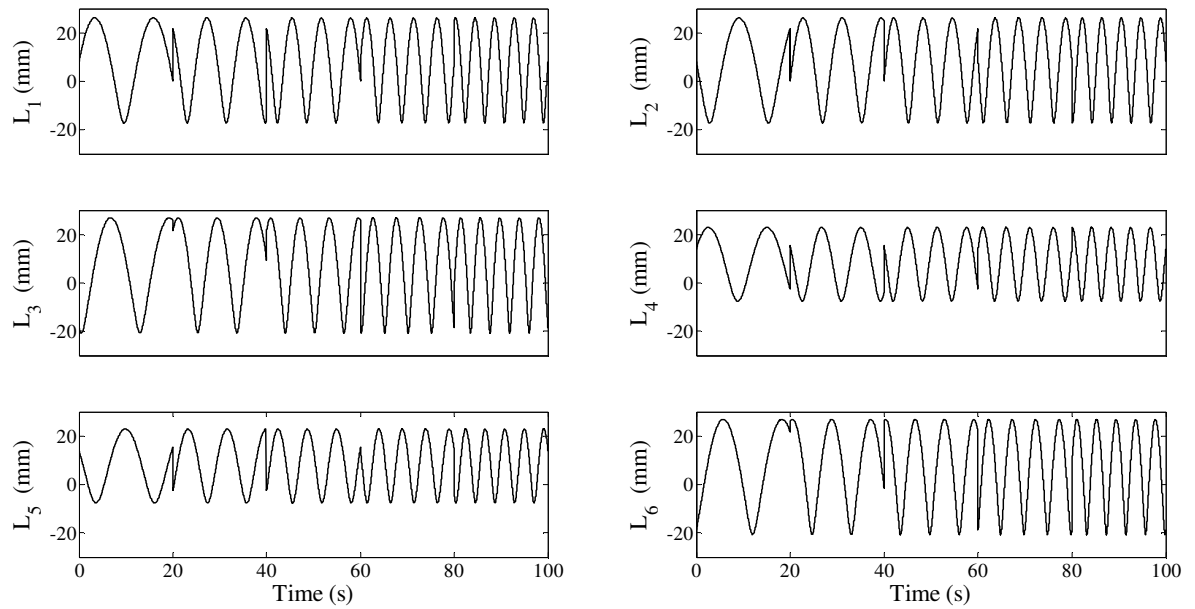


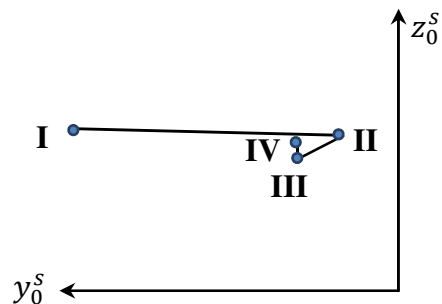
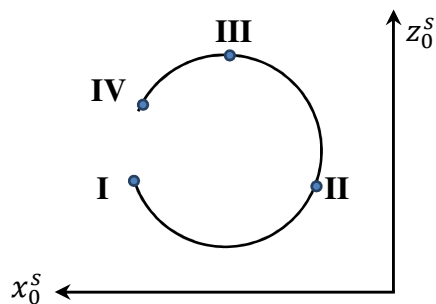
Figure 7.3 Actuator displacements of 6-DOF Stewart platform.

7.2.3. Control scheme

Performance of the force augmentation scheme was re-evaluated in the presence of base excitation, as described above. The effectiveness of the system was validated by emulating two live-line maintenance tasks. First, the performance of the telemanipulator was evaluated when the haptic device applied no force to the operator's hand (NF). The same tests were repeated when the operator ran the system under force augmentation scheme (AU) whereby the haptic device utilized the AU force.

7.3. Test Procedure

A total number of $2(\text{force modes}) \times 2(\text{tasks}) \times 3(\text{trials}) \times 8(\text{participants}) \times 2(\text{networks}) = 192$ trials were collected. There were eight students from the University of Manitoba who contributed in this study. They had experience with haptic device, and were familiar with the live-line maintenance activities. All participants were right-handed, and reported a normal to corrected-to-normal vision. The training phase was completed once the operator felt comfortable and confident to use the system. The two tasks are shown in Figure 7.4. As illustrated in Figure 7.4a, the first task was to twist a tie wire around an electrical cable, a semi-circular curve, in $x_0^s z_0^s$ plane (Task A in Figure 7.4) is traced. In Task B (Figure 7.4b), the operator followed a combination of several lines, in $y_0^s z_0^s$ plane, to pull the cotter pin out. In each task, the operator moved the haptic implement along depicted trajectory from point **I** to point **IV**.



(a) Twisting a tie wire (Task A)



(b) Pulling out a cotter pin (Task B)

Figure 7.4 Maintenance tasks used to evaluate performances.

7.4. Results

Figure 7.5 illustrates a typical trajectory of the slave manipulator end-effector when an operator performed Task A, and the system utilized the force augmentation scheme. The trajectory under no force mode is shown in Figure 7.6. In both figures, the network scenario with the path loss exponent of 2.0 dB was used. Radial position errors for these two typical trials are shown in Figure 7.5c and Figure 7.6c under force augmentation and no force modes, respectively. As observed, by utilizing the augmentation force scheme, the position error was reduced. This is because, when the tool was about to collide with

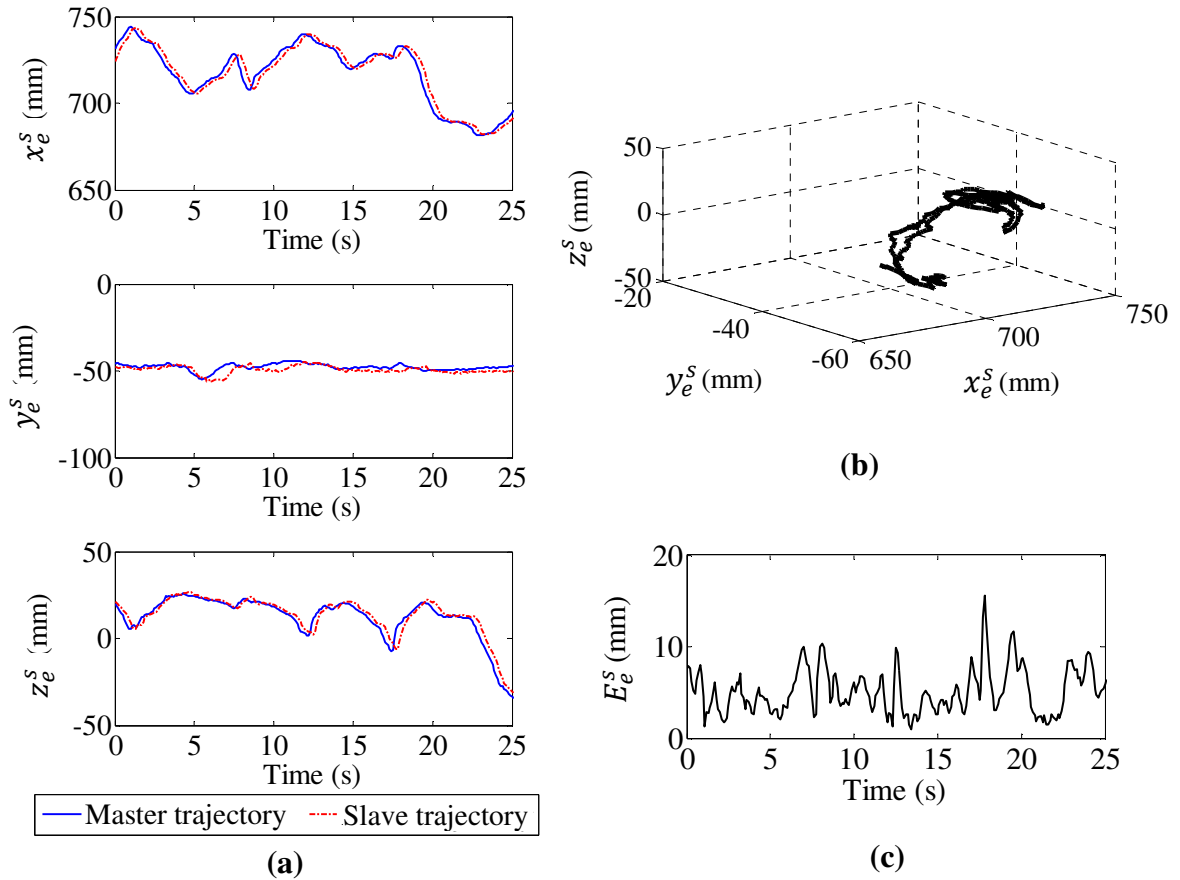


Figure 7.5 Typical trajectory of slave manipulator end-effector under force augmentation mode: (a) along x_0^s , y_0^s and z_0^s axes; (b) 3D view; (c) radial position error of slave end-effector.

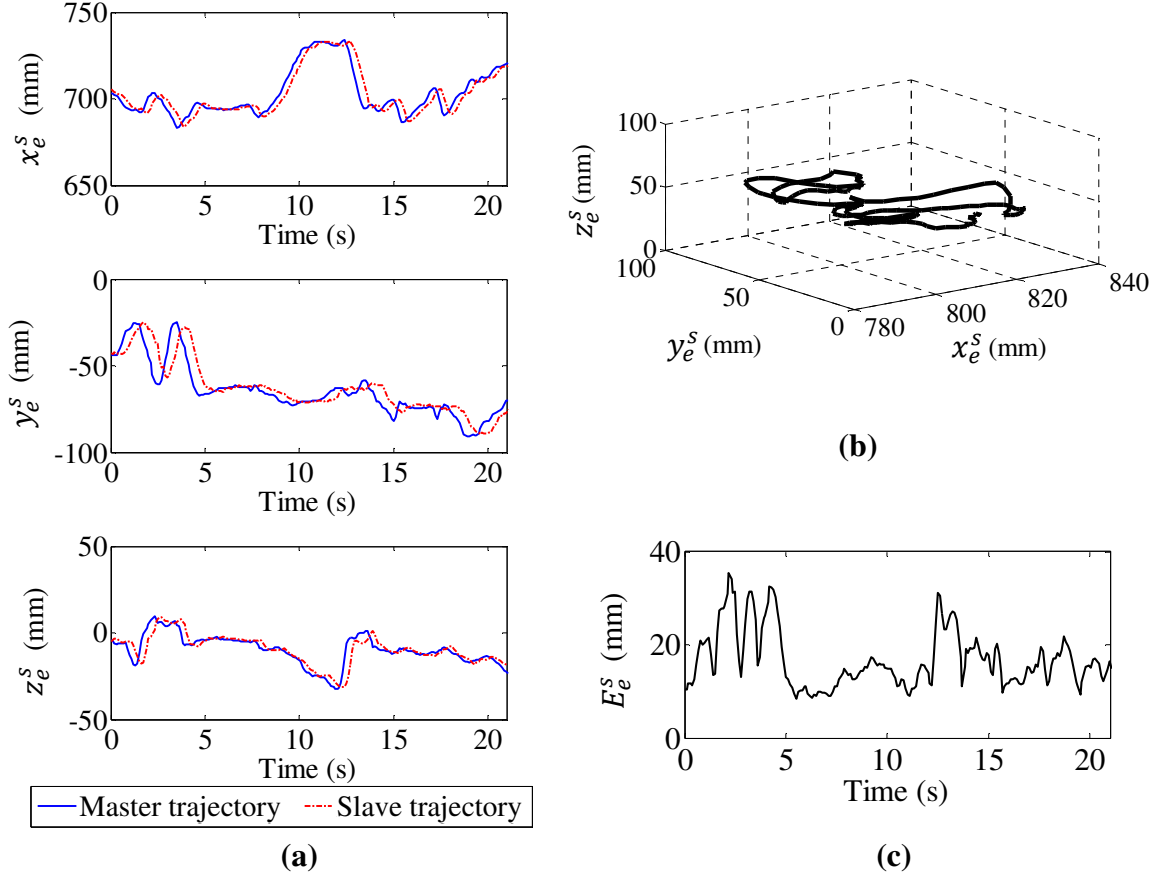


Figure 7.6 Typical trajectory of slave manipulator end-effector under no force mode: **(a)** along x_0^s , y_0^s and z_0^s axes; **(b)** 3D view; **(c)** radial position error of slave end-effector.

the test station, due to the manipulator base movement, the operator abruptly moved the haptic implement to prevent collision. Therefore, position error appeared at the slave end-effector due to the operator's fast motion.

Figure 7.7 and Figure 7.8 show mean values of slave end-effector displacements, over 96 trial runs: 48 trials under NF mode, and 48 trials under AU mode. The slave end-effector displacement is defined as the summation of displacements between two adjacent sampling points along the actual trajectory. As observed, in both tasks, the end-effector travelled longer distance in NF mode (triangles) than AU mode (circles). Larger end-

effector displacement, in turn, results in increasing the operator's effort to perform a task that is not desirable.

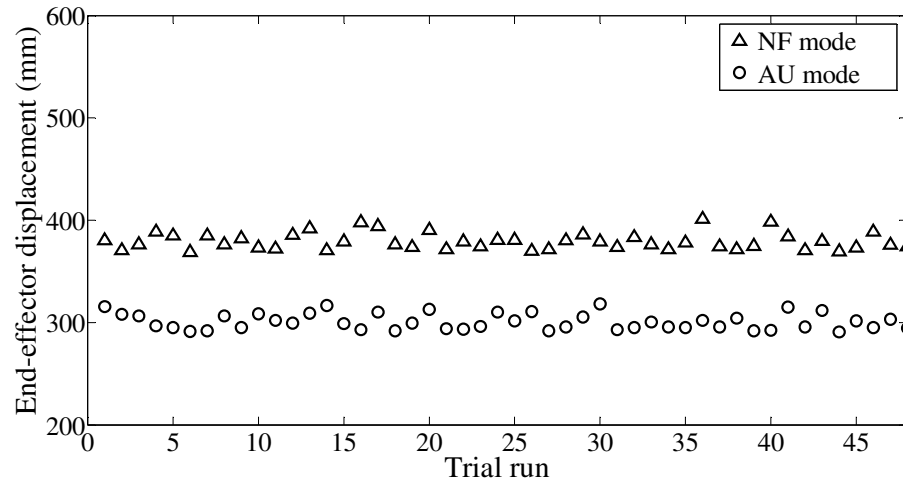


Figure 7.7 Slave end-effector displacements for Task A over 48(trials) $\times$ 2(schemes)=96 trial runs.

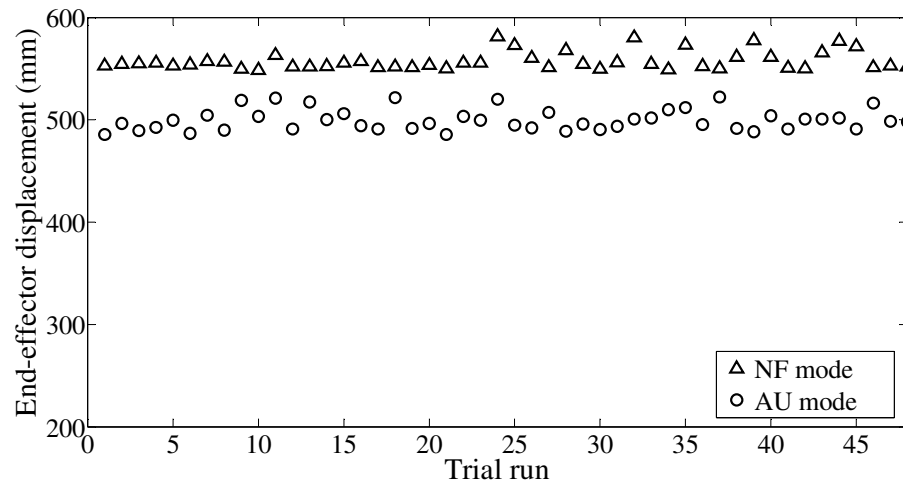


Figure 7.8 Slave end-effector displacements for Task B over 96 trial runs.

Overall information about performance measures is given in Table 7.2. As seen in the fifth column, the number of unsuccessful attempts, in the NF mode, was more than the

AU mode. An unsuccessful attempt was recorded when an operator recognized himself unable to complete the task due to test conditions. More specifically, the operators could not finish the assigned tasks for 13 and 5 times (out of 96) under NF and AU modes, respectively. The AU mode was found better than the NF in terms of the operators' success in completing the tasks. Furthermore, the end-effector travelled longer path in the NF mode (mean value of 465.15 mm) as compared to the VF mode (mean value of 401.14 mm) which in turn resulted in increasing the needed operator's effort to accomplish a task.

Table 7.2 also shows that the mean value of task completion times, in the NF mode (18.29 s), was less than AU mode (24.99 s). Figure 7.9 and Figure 7.10 depict the task completion times over 96 trial runs, for both tasks and under the two force modes. As shown the NF mode was less time consuming than AU. The reason can be found in the nature of force augmentation scheme, which tends to slow down the hand motion upon position errors appearing at the slave site.

Table 7.2 Performance measures under no force (NF) and force augmentation (AU) modes.

Task	Force mode	Network scenario	Task time (s)	Unsuccessful attempts (%)	End-effector displacement (mm)
Twisting a tie wire (Task A)	NF	$n=2.0$	19.18	16.7	380.91
		$n=3.0$	21.32		365.38
	AU	$n=2.0$	29.46	6.3	290.41
		$n=3.0$	28.71		312.62
Pulling a pin out (Task B)	NF	$n=2.0$	16.56	10.4	548.32
		$n=3.0$	16.09		566.00
	AU	$n=2.0$	21.23	4.2	492.35
		$n=3.0$	20.56		509.19

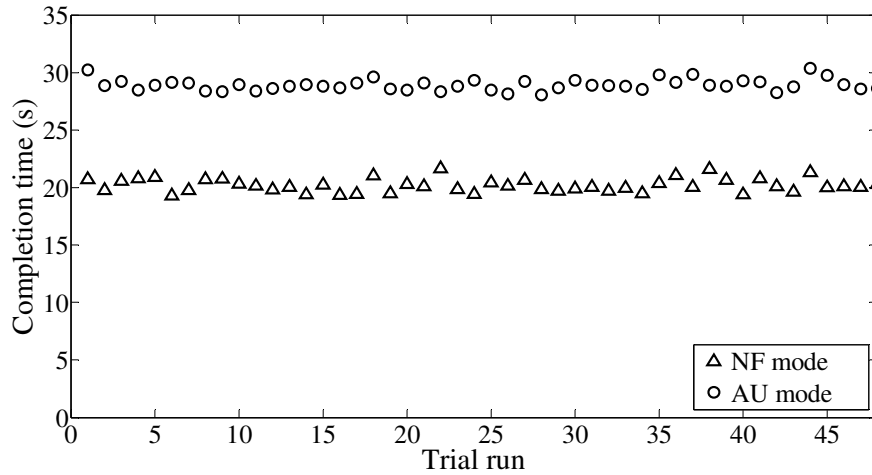


Figure 7.9 Completion times for Task A over 96 trial runs.

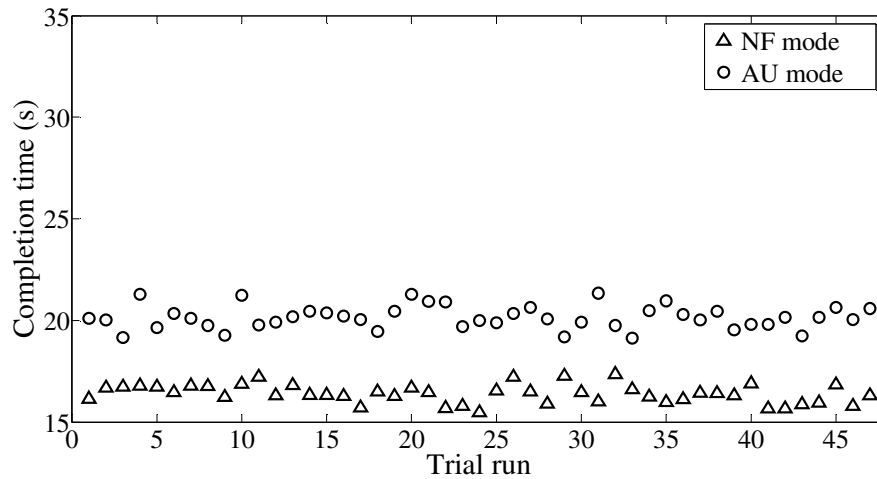


Figure 7.10 Completion times for Task B over 96 trial runs.

Table 7.3 lists values of kurtosis and skewness of the task completion times and position errors at the slave end-effector. As observed, for the NF mode, absolute values of skewness and kurtosis are more than 2. This indicates that the position error at the slave end-effector, as a random variable, does not satisfy the normal distributions criteria. In conclusion, the method of experiment, using NF mode, did not perform well according to the position errors at the slave end-effector. On the contrary, values of kurtosis and

skewness indicate that adding the AU scheme makes the system more reliable than without haptic force.

Table 7.3 Statistical indices for Tasks A and B based on task completion time (TT) and displacement of manipulator end-effector (DE) under two force modes

Scheme	Random variable		Kurtosis	Skewness
No force (NF)	TT (s)	20.25	-1.94	+1.25
	DE (mm)	373.14	+3.15	+4.85
Force Augmentation (AU)	TT (s)	29.09	+0.97	-1.04
	DE (mm)	301.52	+0.95	+0.12

7.5. Summary

This study dealt with performance evaluation of the hydraulic manipulator, retrofitted by a moving platform, when it utilized the force augmentation scheme. Experimental studies were conducted when the manipulator base was excited by the Stewart platform, and the teleoperated slave was controlled wirelessly. There were two sets of experiments. First two maintenance tasks were performed by eight operators when the force capability of the haptic device was deactivated. The operators were then asked to repeat the same tasks when the augmentation force was added to the haptic device. Performance of each mode was evaluated under two measures: number of unsuccessful attempts and displacement of the slave manipulator end-effector. Results indicated that adding the force augmentation scheme helps linemen function more effectively when the system is subject to base-excitation, and communicates through a wireless network. Adding the models of wind conditions, soil, compliance of actuation system, bucket load, and reaction forces can increase the accuracy of the results presented in this chapter.

CHAPTER 8

CONCLUSIONS

8.1. Contributions of This Thesis

The haptic control of base-excited slave hydraulic manipulators, working under delayed and lossy networks, was investigated in this thesis. The targeted application was robot-assisted live-line maintenance. With respect to the application, three main challenges were identified: haptic-enabled teleoperation of hydraulic manipulator, wireless communication between master and slave sites, and excitation of the manipulator base.

Both unilateral and bilateral controls of hydraulic manipulators were thoroughly investigated using experimental validations on actual systems in a laboratory setting. On the bilateral front, a set of experimental studies was conducted on the teleoperated hydraulic actuator to investigate effects of delayed and lossy communication channels on its performance while the system was augmented by several bilateral control schemes. Results were then used to construct a set of performance charts describing the quality of

position and force tracking of the system while it operated under a wireless network. The charts define three regions. Each region allows different combinations of path loss exponent, antenna transmission power, and distance between the master and the slave sites.

With respect to unilateral control, the concept of virtual fixture was shown to reduce master position errors originating from the operator's unwanted hand motion. However, virtual fixtures could not satisfactorily reduce position errors between the master implement and the slave end-effector. Therefore, the concept of position referenced force augmentation scheme, in bilateral mode, was developed to compensate for positioning errors. Combined with virtual fixture force, augmentation force could decrease position errors at both master implement and slave end-effector. Furthermore, the proposed scheme was used to reduce errors appearing due to delays and packet losses in a communication channel. The force augmentation was also found very effective when the manipulator base was excited by a motion platform.

8.2. Future Work

This work could be extended in many ways including, but not limited to, the following subjects:

- (i) When the motion platform generates considerable motions, the dynamics of combined manipulator and platform should be taken into account. The use of integrated dynamics allows us to have more accurate force or position tracking than the separated dynamics.

- (ii) Since the use of force sensors at the end-effector of hydraulic manipulator is impossible in practice, the pressure information of each actuator can be used to estimate the interaction force and be used in the control scheme.
- (iii) Effects of environment phenomena such as wind conditions, soil, compliance of actuation system, bucket load, and reaction forces can be studied in order to generate accurate model of the real bucket movement in a laboratory setting.

Appendix - Questionnaire

Please rate your experience on using the “*Teleoperated Robotic System for Live-Line Maintenance*”. There are no right or wrong answers. We are only seeking your general opinion. Do not put your name on the form.

On each of the following rating scales, please put a cross mark through the line to indicate your assessment. This is an analog scale. It means your answer can be anywhere on the line.

EXAMPLE:

My chances of winning the lottery are:

No chance at all _____ Extremely high

If you thought your chances of winning the lottery were very high, you might place your cross mark through the line as follows:

No chance at all _____ About 90% **X** _____ Extremely high

Note: In the following questions, “system” means “Teleoperated Robotic System for Live-Line Maintenance” that you used in the laboratory environment.

- (1) Given my experience with the system, live-line maintenance tasks can be performed using cameras as indirect visual feedback.

Disagree _____ Agree

- (2) I feel safer using the system rather than performing tasks manually.

Disagree _____ Agree

- (3) The completion time of tasks using the system as compared to manual is shorter.

Disagree _____ Agree

- (4) It was easy to understand how the system works in general.

Disagree _____ Agree

- (5) It was easy to learn using the system.

Disagree _____ Agree

- (6) The virtual fixtures’ concept was helpful in performing the tasks.

Disagree _____ Agree

- (7) I experienced less physical labor as compared to manual tasks.

Disagree _____ Agree

- (8) I experienced less mental load as compared to manual tasks.

Disagree _____ Agree

References

- [1] K. Toussaint, N. Pouliot and S. Montambault, "Transmission line maintenance robots capable of crossing obstacles: State-of-the-art review and challenges ahead," *Journal of Field Robotics*, vol. 26, no. 5, p. 477–499, 2009.
- [2] M. E. Kontz and W. J. Book, "Position/rate haptic control of a hydraulic forklift," in *Proceedings of ASME International Mechanical Engineering Congress*, 2003.
- [3] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Journal of Automatica*, vol. 42, no. 12, pp. 2035-2057, 2006.
- [4] K. Zarei-nia, "Haptic-enabled teleoperation of hydraulic manipulators: theory and application," PhD Thesis, University of Manitoba, 2011.
- [5] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Transactions on Robotics and Automation*, vol. 9, no. 5, pp. 624-637, 1993.
- [6] B. Hannaford, "Stability and performance tradeoffs in bi-lateral telemanipulation," in *Proceedings of IEEE International Conference on Robotics and Automation*, Scottsdale, USA, 1989.
- [7] M. E. Kontz, J. Beckwith and W. J. Book, "Evaluation of a teleoperated haptic forklift," in *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Monterey, USA, 2005.
- [8] N. R. Parker, S. E. Salcudean and P. D. Lawrence, "Application of force feedback to heavy duty hydraulic machines," in *Proceedings of IEEE International Conference on Robotics and Automation*, Atlanta, USA, 1993.
- [9] S. Tafazoli, S. E. Salcudean, K. Hashtrudi-Zaad and P. D. Lawrence, "Impedance control of a teleoperated excavator," *IEEE Transactions on Control System Technology*, vol. 10, no. 3, pp. 355-367, 2002.
- [10] M. E. Kontz, M. C. Herrera, J. D. Huggins and W. J. Book, "Impedance shaping for improved feel in hydraulic systems," in *Proceedings of ASME International Mechanical Engineering Congress and Exposition*, Seattle, USA, 2008.
- [11] P. Lawrence, S. Salcudean, N. Sepehri, D. Chan, S. Bachmann, N. Parker, M. Zhu and R. Frenette, "Coordinated and force-feedback control of hydraulic excavators," in *Proceedings of International Symposium on Experimental Robotics IV*, Berlin, Germany, 1997.

- [12] W. Book, H. Lane, L. Love, D. Magee and K. Obergfell, "A novel teleoperated long-reach manipulator testbed and its remote capabilities via the Internet," in *Proceedings of IEEE International Conference on Robotics and Automation*, Minneapolis, USA, 1996.
- [13] K. Zarei-Nia, A. Goharrizi, N. Sepehri and W. Fung, "Experimental evaluation of bilateral control schemes applied to hydraulic actuators: A comparative study," *Transactions of the Canadian Society for Mechanical Engineering*, vol. 33, no. 3, pp. 377-398, 2009.
- [14] Y. Maddahi, N. Sepehri, S. Liao, W. K. Fung and E. Hossain, "Wireless control of a teleoperated hydraulic manipulator: application towards live-line maintenance," in *Proceedings of ASME/BATH 2013 Symposium on Fluid Power & Motion Control*, Sarasota, USA, 2013.
- [15] S. Liao and W. K. Fung, "On network simulation for performance evaluation of real-time Internet-based teleoperation," in *Proceedings of IEEE International Conference on Robotics and Biomimetics*, Karon Beach, Thailand, 2011.
- [16] Y. Maruyama, "Robotic applications for hot-line maintenance," *International Journal of Industrial Robot*, vol. 27, pp. 357-365, 2000.
- [17] J. Chan, "Live work guide for substations," EPRI, (2004) Retrieved 8 December 2008.
- [18] K. Takaoka, K. Yokoyama, H. Wakisako, K. Yano, K. Higashijima and S. Murakami, "Development of the fully-automatic live-line maintenance robot-phase III," in *Proceedings of International Symposium on Assembly and Task Planning*, Fukuoka, Japan, 2001.
- [19] S. Montambault and N. Pouliot, "The HQ LineROVer: Contributing to innovation in transmission line maintenance," in *ESMO Proceedings: the Power is in Your Hands*, 2003.
- [20] K. Tsukahara, Y. Tanaka, Y. He, R. Hori, K. Mano, A. Hibino, Y. Taru and K. Tatsuno, "An experimental robot system for power distribution line maintenance robots - system architecture and bolt insertion experiment," in *Proceedings of IEEE International Conference in Intelligent Robots and System*, Nice, France, 2008.
- [21] R. Aracil, L. F. Penin, M. Feme, L. M. Jimenez, A. Barrientos, A. Santamaria, P. Martinez and A. Tudun, "ROBTET: A new teleoperated system for live-line maintenance," in *Proceedings of IEEE International Conference on Transmission and Distribution Construction, Operation and Live-line Maintenance*, Columbus, USA, 1995.

- [22] S. Lu, P. Ma, L. Bingqiang and X. BiCui, "Live woking robot for power distribution systems," in *Proceedings of International Conference on Control and Automation*, Montreal, Canada, 2003.
- [23] O. Y. Ming, D. V. Beard and F. P. Brooks Jr., "Force display performs better than visual display in simple 6-D docking task," in *Proceedings of IEEE Conference on Robotics and Automation*, Scottsdale, USA, 1989.
- [24] M. C. Yip, M. Tavakoli and R. Howe, "'Performance analysis of a haptic telemanipulation task under time delay," *Journal of Advanced Robotics*, vol. 25, no. 5, pp. 651-673, 2012.
- [25] A. Hamam, M. Eid and A. El Saddik, "'Effect of kinesthetic and tactile haptic feedback on the quality of experience of edutainment applications," *Journal of Multimedia Tools and Applications*, vol. 67, pp. 455-472, 2013.
- [26] S. Hyoungh, L. Chuang, K. Junsuk and H. Bulthoff, "Haptic feedback cues can improve human perceptual awareness in multi-robots teleoperation," in *Proceedings of IEEE International Conference on Control, Automation and Systems*, Gyeonggi-do, Korea, 2011.
- [27] G. Clement, "An overview of CAT control in nuclear services," in *Proceedings of IEEE International Conference on Robotics and Automation*, 1985.
- [28] M. Tavakoli, Patel, R. V. and M. Moallem, "A force reflective master-slave system for minimally invasive surgery," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, USA, 2003.
- [29] A. J. Madhani, "The Black Falcon: a teleoperated surgical instrument for minimally invasive surgery," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, Victoria, Canada, 1998.
- [30] L. Sun, F. Van Meer, Y. Bailly and C. K. Yeung, "Design and development of a da Vinci surgical system simulator," in *Proceedings of IEEE International Conference on Mechatronics and Automatio*, Harbin, China, 2007.
- [31] A. Baheti, "RoSS: virtual reality robotic surgical simulator for the da Vinci surgical system," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Reno, USA, 2008.
- [32] Y. Matsumoto, "Dexterous manipulation in constrained bilateral teleoperation using controlled supporting point," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 2, pp. 1113-1121, 2007.

- [33] F. Najafi and N. Sepehri, "A novel hand-controller for remote ultrasound imaging," *Journal of Mechatronics*, vol. 18, no. 10, pp. 578-590, 2008.
- [34] J. Funda, "A symbolic teleoperator interface for time-delayed underwater robot manipulation," in *Proceedings of Ocean Technologies and Opportunities in the Pacific for the 90's*, 1991.
- [35] N. Diolaiti and M. Claudio, "Teleoperation of a mobile robot through haptic feedback," in *Proceedings of IEEE International Workshop on Haptic Virtual Environments and their Applications*, 2002.
- [36] S. G. Hong, "Generating artificial force for feedback control of teleoperated mobile robots," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, Kyongju, Korea, 1999.
- [37] J. Lim, J. Ko and J. Lee, "Internet-based teleoperation of a mobile robot with force-reflection," in *Proceedings of IEEE Conference on Control Applications*, 2003.
- [38] O. J. Rosch, K. Schilling and H. Roth, "Haptic interfaces for the remote control of mobile robots," *Journal of Control Engineering Practice*, vol. 10, pp. 1309-1313, 2002.
- [39] M. Boukhniher, "Scaled teleoperation controller design for micromanipulation over Internet," in *Proceedings of IEEE International Conference on Robotics and Automation*, New Orleans, USA, 2004.
- [40] S. H. Ahn, H. S. Jung, Y. K. Kim and H. R. Kim, "A compliance control for position referenced bilateral control systems," in *Proceedings of International Conference on Intelligent Systems and Control*, Cambridge, USA, 2006.
- [41] L. B. Rosenberg, "Virtual fixtures: perceptual tools for telerobotic manipulation," in *Proceedings of IEEE Annual International Symposium on Virtual Reality*, Seattle, USA, 1993.
- [42] Y. Maddahi, R. A. Rahman, W. K. Fung and N. Sepehri, "Effect of network quality on performance of bilateral teleoperated hydraulic actuators: a comparative study," *Control and Intelligent Systems*, vol. 41, no. 1, pp. 11-25, 2013.
- [43] H. Hayn and D. Schwarzmam, "Control concept for a hydraulic mobile machine using a haptic operating device," in *proceedings of International Conferences Advances in Computer-Human Interactions*, Cancun, Mexico, 2009.
- [44] J. J. Abbott, G. D. Hager and A. M. Okamura, "Steady-hand teleoperation with virtual fixtures," in *Proceedings of IEEE International Workshop on Robot and*

Human Interactive Communication, Millbrae, USA, 2003.

- [45] M. Diaz-Cacho, A. Fernandez, M. Garcia and A. Barreiro, "Internet emulation system for UDP-based teleoperation," in *Proceedings of Mediterranean Conference on Control and Automation*, Ajaccio, France, 2008.
- [46] Nessoft Knowledge Base Company, "Packet loss or latency at intermediate hops," 2010.
- [47] G. Matz and F. Hlawatsch, "Wireless Communications over Rapidly Time-Varying Channels," in *Fundamentals of time-varying communication channels*, Amsterdam, The Netherlands: Academic Press, 2011, p. 1–63.
- [48] A. Suzuki and K. Ohnishi, "Frequency-domain damping design for time-delayed bilateral teleoperation system based on modal space analysis," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 1, pp. 177-190, 2013.
- [49] A. Onat, T. Naskali, E. Parlakay and O. Mutluer, "Control over imperfect networks: model-based predictive networked control systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 3, pp. 905-913, 2011.
- [50] W. R. Ferrell, "Remote manipulation with transmission delay," *IEEE Transactions on Human Factors in Electronics*, Vols. HFE-6, pp. 24-32, 1965.
- [51] R. Anderson and M. Spong, "Bilateral control of teleoperators with time delay," *IEEE Transactions on Automatic Control*, vol. 34, no. 5, pp. 494-501, 1989.
- [52] G. Niemeyer and J. Slotine, "Stable adaptive teleoperation," *IEEE Journal of Oceanic Engineering*, vol. 16, no. 1, pp. 152-162, 1991.
- [53] G. M. H. Leung, B. A. Francis and B. Apkarian, "Bilateral controller for teleoperators with time delay via μ -synthesis," *IEEE Transaction on Robotics and Automation*, vol. 11, no. 1, pp. 105-116, 1995.
- [54] A. Birouche, B. Mourllion and M. Basset, "Model reduction for discrete-time switched linear time-delay systems via the H_∞ robust stability," *Journal of Control and Intelligent Systems*, vol. 39, pp. 78-86, 2011.
- [55] W. Kim, B. Hannaford and A. Fejczy, "Force-reflection and shared compliant control in operating telemanipulators with time delay," *IEEE Transactions on Robotics and Automation*, vol. 8, no. 2, pp. 176-185, 1992.
- [56] S. Munir and W. Book, "Internet-based teleoperation using wave variables with prediction," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 124-133, 2002.

- [57] E. Rodríguez-Seda, D. Lee and M. Spong, "Experimental comparison study of control architectures for bilateral teleoperators," *IEEE Transactions on Robotics*, vol. 25, no. 6, pp. 1304-1318, 2009.
- [58] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Journal of Robotics and Autonomous Systems*, vol. 38, no. 1, pp. 49-64, 2002.
- [59] M. Guiatni, A. Kheddar and H. Melouah, "Sliding mode bilateral control and four channels scheme control of a force reflecting master/slave teleoperator," in *proceedings of IEEE International Conference on Mechatronics and Automation*, Niagara Falls, Canada, 2005.
- [60] I. Aliaga, A. Rubio and E. Sanchez, " Experimental quantitative comparison of different control architectures for master-slave teleoperation," *IEEE Transactions on Control Systems Technology*, vol. 12, no. 1, pp. 2-11, 2004.
- [61] A. Aziminejad, M. Tavakoli, R. Patel and M. Moallem, "Wave-based time delay compensation in bilateral teleoperation: Two-channel versus four-channel architectures," in *Proceedings of American Control Conference*, New York, USA, 2007.
- [62] W. R. Ferrell, "Remote manipulation with transmission delay," *IEEE Transactions on Human Factors in Electronics*, vol. HFE6, pp. 24-32, 1965.
- [63] T. B. Sheridan and W. R. Ferrell, "Remote manipulative control with transmission delay," *IEEE Transactions on Human Factors in Electronics*, vol. HFE4, no. 1, pp. 25-29, 1963.
- [64] T. Sheridan, *Telerobotics, Automation and Human Supervisory Control*, MIT Press, 1992.
- [65] C. Sayers, *Remote Control Robotics*, New York: Springer Verlag, 1999, pp. 41-50.
- [66] I. Farkhatdinov and J. A. J. Ryu, "Preliminary experimental study on haptic teleoperation of mobile robot with variable force feedback gain," in *Proceedings of IEEE Haptics Symposium*, Waltham, USA, 2010.
- [67] D. Lee, O. Martinez-Palafox and M. W. Spong, "Bilateral teleoperation of a wheeled mobile robot over delayed communication network," in *Proceedings of IEEE International Conference on Robotics and Automation*, Orlando, USA, 2006.
- [68] E. Slawinski, V. A. Mut and J. F. Postigo, "Teleoperation of mobile robots with time varying delay," *IEEE Transactions on Robotics*, vol. 23, no. 5, p. 1071-1082,

2007.

- [69] E. Slawinski and V. A. Mut, "Control scheme including prediction and augmented reality for teleoperation of mobile robots," *Journal of Robotica*, vol. 28, no. 1, p. 11–22, 2010.
- [70] Y. Song, H. Wang, Y. Jiang and L. Ling, "AApe-D: a novel power transmission line maintenance robot for broken strand repair," in *Proceedings of International Conference on Applied Robotics for the Power Industry (CARPI)*, Zurich, Switzerland, 2012.
- [71] J. Jian, Z. Guoxian and Z. Tingyu, "Design of a mobile robot for the innovation in power line inspection and maintenance," in *Proceedings of International Conference on Reconfigurable Mechanisms and Robots*, London, UK, 2009.
- [72] J.-Y. Park, J.-K. Lee, B.-H. Cho and K.-Y. Oh, "Development of inspection robot system for live-line suspension insulator strings in 345kV power transmission lines park," in *Proceedings of European Conference on Power Electronics and Applications*, Barcelona, Spain, 2009.
- [73] K. Takaoka, K. Yokoyama, H. Wakisako, K. Yano, K. Higashitima and S. Murakami, "Development of the fully-automatic live-line maintenance robot-phase III," in *Proceedings of IEEE International Symposium on Assembly and Task Planning Soft Research Park*, Fuluoka, Japan, 2009.
- [74] T. Issariyakul and E. Hossain, *Introduction to network simulator NS2*, Springer, 2009.
- [75] M. Karpenko, N. Sepehri and J. Anderson, "Decentralized coordinated motion control of two hydraulic actuators handling a common object," *Journal of Dynamic Systems, Measurement and Control*, vol. 129, pp. 729-741, 2007.
- [76] H. E. Merritt, *Hydraulic control systems*, NY: John Wiley, 1967.
- [77] N. Niksefat, N. Sepehri and Q. Wu, "Design and experimental evaluation of a QFT contact task controller for electro-hydraulic actuators," *International Journal of Robust and Nonlinear Control*, vol. 17, pp. 225-250, 2007.
- [78] L. Márton, S. Fodor and N. Sepehri, "A practical method for friction identification in hydraulic actuators," *Journal of Mechatronics*, vol. 21, p. 350–356, 2011.
- [79] M. Jerouane, N. Sepehri and F. Lamnabhi-Lagarigue, "Dynamic analysis of variable structure force control of hydraulic actuators via the reaching law approach," *International Journal of Control*, vol. 77, pp. 1260-1268, 2004.

- [80] L. An and N. Sepehri, "Leakage fault detection in hydraulic actuators subject to unknown external loading," *Journal of Fluid Power*, vol. 9, pp. 15-25, 2008.
- [81] K. Zarei-nia, N. Sepehri, T. Olson and W. Mueller, "Haptic-enabled control of hydraulic manipulators applied to power line maintenance: concept implementation," in *Proceedings of International Conference on Applied Robotics for the Power Industry*, Montreal, Canada, 2010.
- [82] Y. Maddahi, K. Zareinia, N. Sepehri, T. Olson and W. Mueller, "Live-line maintenance training using robotics technology," in *Proceedings of IEEE World Haptics Conference*, Korea, 2013.
- [83] J. Denavit and R. S. Hartenberg, "A kinematic notation for lower-pair mechanisms based on matrices," *ASME Journal of Applied Mechanics*, vol. 23, pp. 215-221, 1995.
- [84] E. Fitcher, "A Stewart platform-based manipulator: General theory and practical construction," *International Journal of Robotics Research*, vol. 5, no. 2, pp. 157-182, 1986.
- [85] N. Sepehri, A. Khayyat and B. Heinrichs, "Development of a nonlinear PI controller for accurate positioning of an industrial hydraulic manipulator," *Journal of Mechatronics*, vol. 7, no. 8, pp. 683-700, 1997.
- [86] P. Prokopiou, S. Tzafestas and W. Harwin, "A novel scheme for human-friendly and time-delays robust neuropredictive teleoperation," *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 25, pp. 311-340, 1999.
- [87] M. H. Zadeh, D. Wang and E. Kubica, "Factors affecting the perception-based compression of haptic data," Intech Publication, 2010, pp. 517-542.
- [88] TATA Consultancy Services Ltd, "WANem 2.0: Wide area network emulator," 2011. [Online]. [Accessed 2011].
- [89] S. Hemminger, "Network emulation with NetEm," in *Proceedings of the Australia's 6th National Linux Conference*, 2005.
- [90] R. Oboe, "Force-reflecting teleoperation over the Internet: the JBIT project," *Proceedings of the IEEE*, vol. 91, no. 3, pp. 449-462, 2003.
- [91] Z. Li and D. Constantinescu, "Remote dynamic proxies for wave-based peer-to-peer haptic interaction," in *Proceedings of International Conf. on World Haptics Interfaces*, Salt Lake City, USA, 2009.

- [92] H. Larijani and K. Radhakrishnan, "Voice quality in VoIP networks based on random neural networks," in *Proceedings of International Conference on Networks*, Menuires, France, 2010.
- [93] J. Colmenares, K. Kim, Z. Zhang, C. Lim and K. Rim, "Real-time component based software architecture for QoS-adaptive networked multimedia applications," in *Proceedings of IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing*, Carmona, Spain, 2010.
- [94] L. Breslau, D. Estrin, K. Fall, S. Floyd, J. Heidemann, A. Helmy, P. Huang, S. McCanne, K. Varadhan, X. Ya and Y. Haobo, "Advances in network simulation," *Journal of Computer*, vol. 33, no. 5, pp. 59-67, 2000.
- [95] K. M. Reineck, *Evaluation and comparison of network simulation tools*, M.Sc. Thesis, Institute for Open Communication Systems, 2008.
- [96] S. McCanne and V. Jacobson, "The BSD packet filter: a new architecture for user-level packet capture," in *Proceedings of the USENIX Winter Conference*, 1993.
- [97] K. Fall, "Network emulation in the VINT/NS simulator," in *Proceedings of IEEE Symposium on Computers and Communications*, Read Sea, 1999.
- [98] S. Ivanov, A. Herms and G. Lukas, "Experimental validation of the NS-2 wireless model using simulation, emulation, and real network.," in *Proceedings of ITG-GTI Conference on Communication in Distributed Systems*, Bern, Switzerland, 2007.
- [99] G. Sankaranarayanan and B. Hannaford, "Experimental comparison of Internet haptic collaboration with time-delay compensation techniques," in *Proceedings of IEEE International Conf. on Robotics and Automation*, Pasadena, USA, 2008.
- [100] S. Sirouspour and A. Shahdi, "Model Predictive Control for Transparent Teleoperation Under Communication Time Delay," *IEEE Transactions on Robotics*, vol. 22, no. 6, pp. 1131-1145, 2006.
- [101] G. Niemeyer and J. E. Slotine, "Telemanipulation with time delays," *Journal of Robotics Research*, vol. 23, pp. 873-890, 2004.
- [102] D. Kotz, C. Newport, R. Gray, J. Liu, Y. Yuan and C. Elliott, "Experimental evaluation of wireless simulation assumptions," in *Proceedings of ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, New York, USA, 2004.
- [103] I. Eltahir, "The impact of different radio propagation models for mobile ad hoc networks (MANET) in urban area environment," in *Proceedings of International Conference on Wireless Broadband and Ultra Wideband Communications*,

Sydney, Australia, 2007.

- [104] T. Rappaport, *Wireless communications: principles and practice*, Prentice Hall, 2002.
- [105] D. C. Cox, R. Murray and A. Norris, "800 MHz attenuation measured in and around suburban houses," *AT&T bell Laboratory Technical Journal*, vol. 673, no. 6, 1984.
- [106] M. Karpenko and N. Sepehri, "Quantitative fault tolerant control design for a leaking hydraulic actuator," *Journal of Dynamic Systems, Measurement, and Control*, vol. 132, no. 5, pp. 1-7, 2010.
- [107] N. Turro, O. Khatib and E. Coste-Maniere, "Haptically augmented teleoperation," in *Proceedings of IEEE International Conference on Robotics and Automation*, Seoul, Korea, 2001.
- [108] B. Heinrichs, N. Sepehri and A. Thornton-Trump, "Position-based impedance control of an industrial hydraulic manipulator," *IEEE Control Systems Magazine*, vol. 17, pp. 46-52, 1997.
- [109] D. P. Lawrence, F. Sassani, S. N. Sauder, U. Wallersteiner and J. Wilson, "Computer-assisted control of excavator-based machines," in *International off-highway and powerplant congress and exposition*, 1993.
- [110] K. Zarei-Nia, X. Yang, P. Irani and N. Sepehri, "Evaluating factors that influence path tracing with passive haptic guidance," in *Proceedings of International Conference on Haptic and Audio Interaction Design*, 2009.
- [111] K. L. Wuensch, *Encyclopedia of statistics in behavioral science*, Chichester, UK: Wiley, 2005.
- [112] Y. Maddahi, N. Sepehri, A. Maddahi and M. Abdolmohammadi, "Calibration of wheeled mobile robots with differential drive mechanisms: An experimental approach," *Journal of Robotica*, vol. 30, no. 6, pp. 1029-1039, 2012.
- [113] Y. Maddahi, A. Maddahi and N. Sepehri, "Calibration of omnidirectional wheeled mobile robots," *Journal of Robotica*, vol. 31, no. 6, pp. 969-980, 2013.
- [114] M. B. Wilk and R. Gnanadesikan, "Probability plotting methods for the analysis of data," *Journal of Biometrika*, vol. 55, no. 1, p. 1-17, 1968.
- [115] K. Natori, T. Tsuji, K. Ohnishi, A. Hase and K. Jezernik, "Robust bilateral control with Internet communication," in *Proceedings of IEEE Conference on Industrial Electronics Society*, Busan, Korea, 2004.

- [116] K. H. Suny, H. Momeni and F. J. Sharifi, "Model reference adaptive control design for a teleoperation system with output prediction," *Journal of Intelligent and Robotic Systems*, vol. 59, no. 3-4, pp. 319-339, 2010.
- [117] D. Chen, X. Tang, N. Xi, Y. Wang and H. Li, "Stability analysis for Internet based teleoperated robot using prediction control," in *Proceedings of IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems*, 2011.
- [118] E. Kamrani, "Real-time Internet-based teleoperation," *Journal of Intelligent Control and Automation*, vol. 3, pp. 356-375, 2012.
- [119] CISCO, 2010. [Online]. Available:
https://www.cisco.com/en/US/prod/collateral/wireless/ps7183/ps469/data_sheet_ant2440nv.pdf.