Investigation of Wave Variable Control on Bilateral Teleoperation System with Constant Time Delays

by

Xizhe Sun
B.Eng., Dalian Ocean University, 2015

A Report Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF ENGINEERING

in the Department of Mechanical Engineering

Investigation of Wave Variable Control on Bilateral Teleoperation System with Constant Time Delays

by

Xizhe Sun
B.Eng., Dalian Ocean University, 2015

Supervisory Committee

Dr. Daniela Constantinescu, Supervisor
(Department of Mechanical Engineering)

Dr. Caterina Valeo, Departmental Member
(Department of Mechanical Engineering)

Supervisory Committee

Dr. Daniela Constantinescu, Supervisor
(Department of Mechanical Engineering)

Dr. Caterina Valeo, Departmental Member
(Department of Mechanical Engineering)

ABSTRACT

Teleoperation Systems allow human operators to perform complex tasks in remote and hazardous environments. A wide variety of applications based on teleoperation systems, including space exploration, undersea detection, minimally invasive surgery etc. have made great contributions to our society. Various feedbacks like sound, visual and haptic feedbacks are sent to the user in order to enhance the user experience and improve system performance. With the help of haptic feedbacks, human operators can achieve remote control and interact with an inaccessible environment. However, time delays between the master and the slave may cause instability. To guarantee the stability and improve the transparency, many approaches such as passivity-based control, adaptive control, robust control, and sliding mode control are widely researched. This project studied Wave Variable Control approach in teleoperation systems, one of passivity-based control theories, and discussed its advantages and disadvantages.

Contents

List of Tables

List of Figures

ACKNOWLEDGEMENTS

I would like to thank:

My Supervisor Dr. Daniela Constantinescu who gave me a great opportunity to work on this project under her supervision. During this project, I have learnt a lot of control theories and simulation.

My parents who always support me during my ups and downs in Canada. I will never forget their selfless and generous support to my whole master studies, especially when I met troubles and felt hopeless. I could never achieve my goals without their love and guidance.

My co-op managers and mentors , their requirements and advice helped me become a professional software engineer.

DEDICATION

Prepare to survive in the workplace next step!

Chapter 1

Introduction

According to [12], a teleoperation system consists of five subsystems: the human operator, the master robot, the communication channel, the slave robot, and the environment, as shown in Fig.1.1

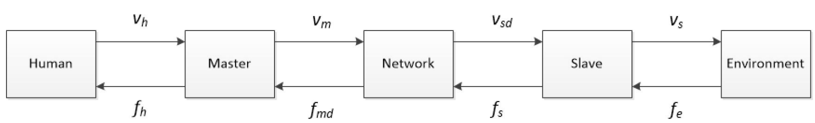


Figure 1.1: teleoperation system

In such a system, human operator inputs a position/velocity command forward through the master robot, communication channel, the slave robot, and then to the environment. On the other side, the contact force sensed at the environment are transmitted back to the human operator through these blocks to improve system performance and offer position tracking. Ideally, in the steady state, the slave velocity V_s should be equal to the master velocity V_m, and the force F_m applied at the master should be equal to the environment force F_e, and all of them should reach a steady state to keep the system stable. The slave robot should be able to follow the master robot accurately, in other words, the motions between master and slave robots should be synchronized.

1.1 Stability, Transparency

To represent the relationship of force and velocity in a teleoperation system, a Two-port network model is shown in Fig.1.2

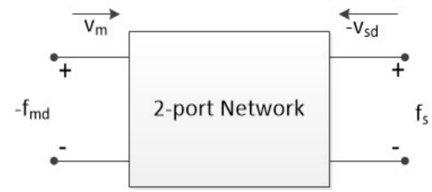


Figure 1.2: A Two-port network model in a teleoperation system

Stability and transparency are two main considerations when designing a teleoperation system. A teleoperation system with interconnections of all passive elements is passive and thus is stable [7]. Another important concept, transparency, provides the human with a feeling of the remote environment [1]. A teleoperation system is defined to be transparent if the human operator perceives the remote environment accurately and performs the remote task with ease [8]. Ideally, the teleoperation system would be completely transparent, so human operators feel that they are directly interacting with the remote task [2]. However, maintaining stability and transparency at the same time is always a challenging task and hot research topic, since there is a trade-off between stability and transparency. Improving stability will always sacrifice transparency, and vice versa [2].

In a perfect teleoperation system, there is no time delay so there is no stability issue. However, in practice, time delays in the communication channel always exist due to signal transmission speed and channel bandwidth, especially when teleoperation is performed over a long distance like undersea and outerspace operation [8]. The teleoperation system can become unstable even under small time delays [6].

1.2 Passivity

According to [2], passivity is a sufficient condition for the stability of a system. If a teleoperation system is passive, it is guaranteed to be stable. However, if a system is stable, it is not necessary to be passive [8]. Using the passivity approach provides an approach guarantee stability of a system [4].

1.3 Contributions

This project aimed at discussing the advantages and disadvantages of a passivity-based control approach, namely the wave variable control, and its effects on bilateral teleoperation system with time delays by implementing current research results. In particular,

1. Studying the stability and transparency in the wave variable control method in bilateral teleoperation with constant time delay.
2. Studying the main negative effects of wave variable control, i.e. wave reflection and position drift, then investigate and compare current methods to reduce wave reflection and position drift.
3. Studying the effects of low pass filter(LPF) to deal with position drift.
4. Discussing how the control parameters affect performance of the wave-variables based bilateral teleoperation system.
5. Simulating the above algorithms in MATLAB/Simulink and analyze their transient response.

1.4 Outline

This report is structured as follows:

Chapter 1 introduces some basic concepts like teleoperation systems, bilateral teleoperation, passivity, stability, transparency etc.

Chapter 2 focuses on the mathematical model of the dynamic teleoperation system and especially on the theoretical foundations of the standard wave variable method and wave controllers. It introduces some core concepts of wave variable control and analyzes its application in bilateral teleoperation. It discusses several methods to reduce the negative effects such as wave reflection and position drift to improve haptic perception, like low pass filter(LPF), and impedance matching. It also analyzes the pros and cons of each method under constant time delays.

Chapter 3 focuses on simulation setups and results based on theories in Chapter 2.

Chapter 4 concludes the report, discusses the limitations and gives an overview of the future work.

Chapter 2

Theoretical Foundations of Wave Variable Control

In this chapter, theoretical and mathematical foundations of wave variable approach are discussed based on current research results. First, we give an overview of the mathematical model of a teleoperation system, and introduce the wave variable approach proposed by *Niemeyer and Slotine et al.* [5]. Next, the stability of wave variable control is studied mathematically. Then, we study the main disadvantages of this method such as wave reflection and position drift. In order to reduce position drift, we study the wave filtering method proposed by *Yongqiang and Peter et al.* [11].

2.1 Mathematical Model of a Teleoperation System

Teleoperation is a remote control technology where users use a master device to operate and control a slave device remotely to follow the user's instructions to achieve certain remote control purposes. Normally, in a teleoperation system, the position and velocity commands from the master robot are transmitted to the slave controller via the communication channel or network. The slave robot is controlled by the slave controller to make contact with the environment, and then the force feedback from the slave side is transmitted back to the master side. Since the master and slave robots can be modeled as a mass-damper system, the mathematical model of a position-position architecture for a teleoperation system with constant time delays can be expressed as following equations. For the Master side:

$$M_m \ddot{x}_m(t) + b_m \dot{x}_m(t) = f_h(t) + f_m(t) \tag{2.1}$$

For the Slave side:

$$M_s \ddot{x}_s(t) + b_s \dot{x}_s(t) = f_e(t) + f_s(t) \tag{2.2}$$

Where:
M_m and M_s are the masses of the Master and Slave robots.
b_m and b_s are the damping coefficients of the Master and Slave robots.
$\dot{x}_m(t), \dot{x}_s(t), \ddot{x}_m(t), \ddot{x}_s(t)$, are the velocities and accelerations of the Master and Slave robots respectively.
$f_h(t), f_e(t)$ are the user hand force and environment force.
$f_m(t) = f_{sd}(t) = -f_s(t - t_f)$ is force feedback sent to the Master robot from the Slave robot, t_f is the forward time delay sent from the master to the slave.
$f_s(t)$ is the force from the Slave Controller applied to the Slave robot.
For the Slave Controller:

$$f_s(t) = K_p(x_m(t - t_f) - x_s(t)) + K_v(\dot{x}_m(t - t_f) - \dot{x}_s(t)) \tag{2.3}$$

Where:
$x_m(t), x_s(t)$ are the positions of the master ans Slave robots respectively.
K_p and K_v are the position and velocity gains of the Slave Controller.
t_f is forward time delay sent from the master to the slave.
A communication channel or network connects from the master side to the slave side. For many reasons (such as transmitting distance, telecommunication equipment quality...), time delays always exist in the communication channel which may disturb and even destabilize the teleoperation system [4]. Therefore, the stability and transparency of the teleoperation system with constant time delays will be discussed in the next sections. To address this problem, wave variable and wave encoding mechanism will be introduced in the next section.

2.2 Wave variable and Wave Encoding

A wave-variable teleoperation system architecture is demonstrated in Fig.2.1 as below:

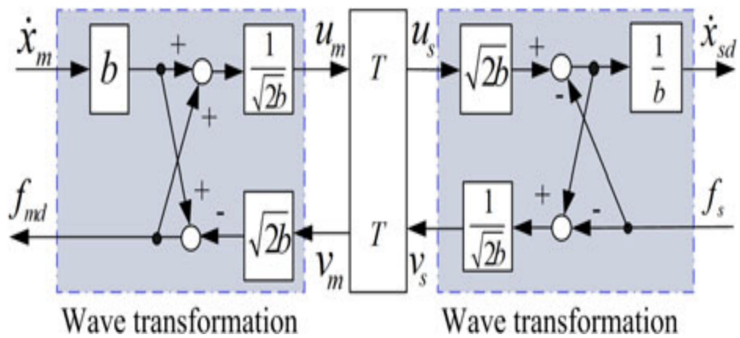


Figure 2.1: Architecture of a wave-variable based teleoperation system, adopted from [3]

Wave variables and wave encoding mechanism were first introduced in [4] based on the passivity theory and scattering approach. Wave variables approach modifies and extends the passivity theory to better deal with time delays in a nonlinear system [4]. Niemeyer and Slotine define the power flow of the input signal as [5]

$$P = \dot{x}^T F = \frac{1}{2}u^T u - \frac{1}{2}v^T v \tag{2.4}$$

Where they define u to be the forward or right moving wave, and v to be the backward or left moving wave [5]. $\frac{1}{2}u^T u$ is the power flowing along forward loop (the main direction) which leads to a positive value of P [5], while $\frac{1}{2}v^T v$ is the power flowing along the backward loop (against the main direction) which generates a negative value of P [5]. The force F and velocity $\dot{x}$ denote the force and velocity of the input signal respectively. According to [5] the pair of wave variables (u, v) can be calculated by pair of power variables $(\dot{x}, F)$ as [5]

$$u = \frac{b\dot{x} + F}{\sqrt{2b}}, v = \frac{b\dot{x} - F}{\sqrt{2b}} \tag{2.5}$$

Where b is the wave impedance. Likewise, the force F and right moving wave u can be computed by using the velocity $\dot{x}$ and left moving wave v as inputs [5]

$$F = b\dot{x} - \sqrt{2b}v, u = -v + \sqrt{2b}\dot{x} \tag{2.6}$$

Here forward moving wave u provides power to the system and should be regarded as a provider of the input signal [5], while backward moving wave v dissipates power from the system and should be regarded as a consumer of the system [5].

2.3 Passivity of Wave Variable Control Approach

As introduced in the first chapter, passivity is a sufficient but not necessary condition to stability [4]. In the power domain, passivity condition can be expressed by [5]

$$\int_0^t P_{in} d\tau = \int_0^t \dot{x}^T F d\tau \geq -E_{store}(0), \forall t \geq 0 \tag{2.7}$$

Where $P_{in}(t)$ is the input power and $E_{store}(0)$ is the initial stored energy [5]. To transfer this passivity condition from power domain into wave domain, assuming that the right moving wave u provides an input while the left moving wave v contains the output [5], the passivity condition in wave domain can be defined as [5]

$$\int_0^t \frac{1}{2} v^T v d\tau \leq \int_0^t \frac{1}{2} u^T u d\tau + E_{store}(0), \forall t \geq 0 \tag{2.8}$$

In this case, Niemeyer and Slotine in [5] found that the control system is passive if the energy in the outgoing wave v is limited to the energy provided by the incoming wave u or stored initially. What they have found interesting is [5] : in the old form in equation (2.7), passivity depends on the product of both variables velocity and force. So if the output variable is delayed, the effect on the product and thus passivity is unpredictable [5]. By contrast, in this new form in equation (2.8), passivity compares only the integration of wave variables u or v over time [5]. Consider a constant time delay T [5]

$$v(t) = u(t - T) \tag{2.9}$$

The passivity condition is satisfied and the stored energy is computed as [5]

$$E_{store}(t) = \int_{t-T}^t \frac{1}{2} u^T u d\tau \tag{2.10}$$

Where $E_{store}(t)$ denotes the input energy stored during the time delay [5]. Since the power dissipation during the time delay is zero, the system does not lose energy [5]. Therefore, for all passive control systems in power domain, they remain passive after wave variable transformation [5]. In addition, since time delays are also passive, we can conclude that wave variable systems are robust to arbitrary constant time delays theoretically [5]. Furthermore, in a teleoperation system, the master and slave robots are generally considered passive. The slave controller (normally a PD controller designed in Velocity-Force Architecture) is normally designed to be passive. The user's behaviours are considered passive, the environment is also passive.
However, since wave variable is a conservative control approach which excessively pursues the passivity of the teleoperation system, the transparency of the wave-variable-based teleoperation system is degraded, as mentioned in Chapter 1 that improving the stability will always sacrifice the transparency of the system, and vice versa. In addition, this approach has two significant drawbacks: wave reflection and position drift. Therefore, solving these two shortcomings of wave variable-based teleoperation system is a critical task in research. Next section will talk about position drift.

2.4 Position Drift

As mentioned in the previous chapter, position drift has become one of the main issues of the wave variable control with constant time delays. Besides the error caused by time delays, position drift make the master and slave devices not synchronized, so the slave robot is not able to follow the master accurately [8]. When the position drift happens, the position error between the delayed Master's position and the Slave controller's position rises [8]. The position error between the left and right sides of a wave variable system can be computed as [5]:

$$\Delta x(t) = x_l(t) - x_r(t) = \frac{1}{\sqrt{2b}} \int_0^t u_l(\tau) + v_l(\tau) - u_r(\tau) - v_r(\tau) d\tau \tag{2.11}$$

Consider a constant time delay T [5]:

$$u_r(t) = u_l(t-T), v_l(t) = v_r(t-T) \tag{2.12}$$

The position error could be [5]:

$$\Delta x_{delay}(t) = \frac{1}{\sqrt{2b}} \int_{t-T}^{t} u_l(\tau) - v_r(\tau) d\tau \qquad (2.13)$$

Ideally, the position error is expected to reach zero if the wave commands were zero for the last T seconds [5]. Unfortunately, such an argument fails or is at least susceptible to numerical errors since it assumes the integration perfect [5]. In fact, any position information must be computed by velocity and time information as [5]:

$$x(t) = \frac{1}{\sqrt{2b}} \int_{t-T}^{t} u_l(\tau) - v_r(\tau) d\tau \qquad (2.14)$$

An initial position error or offset will remain undetected [5]. So in practice the positions may drift from their theoretical values and the system may have slow position drift between the two sides for several reasons: discrete sampling rates, numerical round-off errors, temporary data losses [8]. But these errors are typically very small given digital computers today [5].

Wave integrals can encode position and momentum information just like the wave signals encode velocity and force [5]. The integrated wave variables are defined as [5]:

$$U(t) = \int_0^t u d\tau = \frac{bx + p}{\sqrt{2b}}, V(t) = \int_0^t v d\tau = \frac{bx - p}{\sqrt{2b}} \qquad (2.15)$$

The momentum P can be computed by [5]:

$$P = \int_0^t F d\tau \qquad (2.16)$$

The wave integral transformation do not affect passivity [5]. It is a way to shift the problem from integrating velocity into position to integrating force into momentum [5]. Because of the numerical errors, the position drift exist and in next section we will focus on how to reduce the position drift.

2.5 Wave Reflection

From [8], wave reflection occurs when the impedances are not perfectly matched, circulating reflections will occur in the wave variable teleoperation systems [3]. Wave

reflection issues were first observed and proposed by Niemeyer and Slotine [4] . In order to reduce the wave reflection, Niemeyer and Slotine try to match the master and slave impedance using damping elements [4]. In order to overcome unmodeled impedance changes, Niemeyer adapted wave filters [5] to restrict the bandwidth limitation of the teleoperator. The combination of impedance matching and wave filtering reduces the wave reflections significantly [5].
Wave reflection does not contain any useful information [8]. It can easily result in unpredictable disturbance and disorder, and even make the system unstable [8]. Wave reflections also cause significant oscillation and poor transient response [8].
It is also interesting to note that when a teleoperation system is perfectly matched, the wave variable U_m contains only velocity information and wave variable V_s contains only force information [4]. With the perfectly impedance matched wave teleoperator, the wave variables U_m and wave variable V_s no longer contain components of the incoming wave variables [4]. Therefore, the corresponding circulating wave reflections shown in Fig.2.2 are prevented [11].

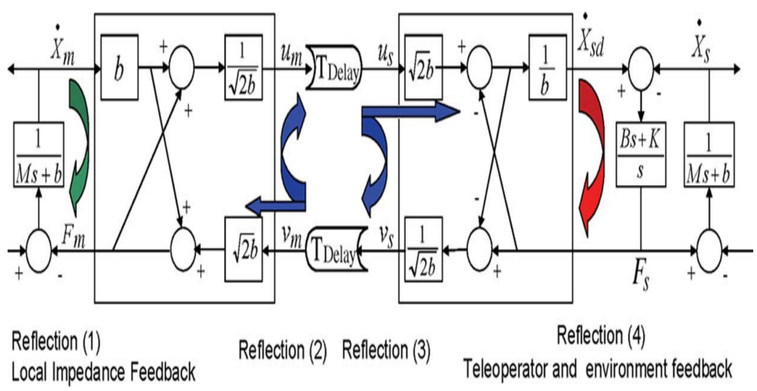


Figure 2.2: Wave reflection in a teleoperation system, adopted from [12]

2.6 Wave Filtering and Low Pass Filter

Wave Filtering is necessary to reduce high frequency noise of the feedback force, but also cause potential risks of instability due to the added phase lag [5]. In this respect, it is closely related to time delays [5]. A wave filter is a first order linear low pass filter (LPF) [5]. Introducing the first order differential equation [5]:

$$\dot{u}_r + \lambda u_r = \lambda u_l \tag{2.17}$$

Where λ is the corresponding bandwidth or cutoff frequency [5]. The energy storage and power dissipation functions are both positive which computed by [5]:

$$E_{store} = \frac{1}{\lambda} u_r^T u_r, P_{diss} = \frac{1}{\lambda^2} \dot{u}_r^T \dot{u}_r \tag{2.18}$$

A low pass filter (LPF) can be added in the forward loop of the standard wave-variable-based teleoperation system in Fig. 2.3 [11]

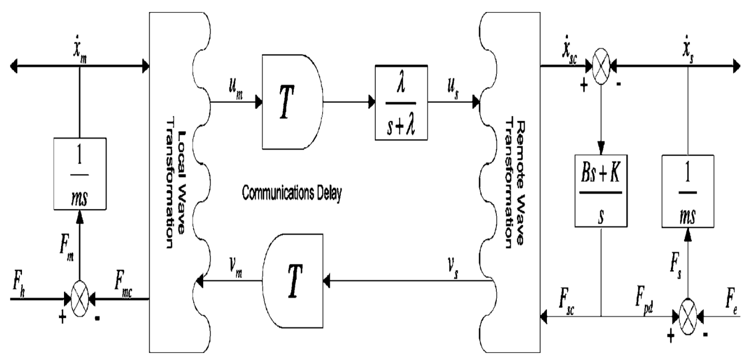


Figure 2.3: Standard wave-variable-based teleoperation system with a low pass filter, adopted from [11]

The filter continually dissipates energy if the wave signal is rapidly changing and so removes any high frequency power [10]. It also stores some power for a nonzero wave signal [10], so that it can smoothly reduce the output even if the input drops suddenly [10] [9].
A first order low pass filter $G(s) = \frac{\lambda}{s+\lambda}$ in Laplace Domain is implemented in the right moving wave path [11]. According to [11], since the magnitude of G(s) is at or below unity for all frequencies, G(s) acts as an energy-dissipating element to dissipate energy at frequencies above the cutoff frequency in the wave loop [11]. As a result, the wave reflections are reduced by G(s) [11]. In addition, external energy inserted into the wave loop will also be dissipated [11] [9]. Considering the passivity of the

system preserved since the following passivity condition is satisfied [11]:

$$\int_0^t \frac{1}{2}u_s^T u_s - \frac{1}{2}v_s^T v_s d\tau \leq \int_0^t \frac{1}{2}u_m^T u_m - \frac{1}{2}v_m^T v_m d\tau + E_{store}(0), \forall t \geq 0 \tag{2.19}$$

Then because the system is passive, the stability of the system can always be guaranteed [11]. In Laplace Domain, since the constant time delay and first order low pass filter are linear [11], the wave variables (u, v) can be calculated by the following Laplace Transform [11]:

$$u_s(t) = \mathcal{L}^{-1}(\frac{\lambda}{s+\lambda}) * u_m(t-T), v_m(t) = v_s(t-T) \tag{2.20}$$

Where $\mathcal{L}^{-1}$ denotes the inverse Laplace transform and $*$ denotes convolution. The wave transmission can be written in terms of the power variables as [11]

$$\dot{x}_s(t) = \mathcal{L}^{-1}(\frac{\lambda}{s+\lambda}) * \dot{x}_m(t-T) - \frac{1}{b}[F_s(t) - \mathcal{L}^{-1}(\frac{\lambda}{s+\lambda}) * F_m(t-T)] \tag{2.21}$$

$$F_m(t) = F_s(t-T) + b[\dot{x}_m(t) - \dot{x}_m(t-T)] \tag{2.22}$$

It can be seen from (2.21) that the second term [11]

$$-\frac{1}{b}[F_s(t) - \mathcal{L}^{-1}(\frac{\lambda}{s+\lambda}) * F_m(t-T)] \tag{2.23}$$

distorts the trajectory tracking [11]. In wave-variable-based teleoperation systems, this distortion will increase significantly with the increase of time delays [11].
In order to remove this distortion of trajectory tracking, Yongqiang and Peter in [11] proposed a method by adding a correcting term on the right moving wave path at the slave side for wave-variable-based teleoperation. An added term [11]

$$\Delta u_s(t) = \frac{1}{\sqrt{2b}}[F_s - \mathcal{L}^{-1}(\frac{\lambda}{s+\lambda}) * F_m(t-T)] \tag{2.24}$$

is inserted into the right moving wave path at the slave side to cancel the bias of the velocity transmission and achieve the best trajectory tracking [11].

2.7 Wave Impedance and Impedance Matching

Niemeyer and Slotine in [5] found that the wave impedance b is a tuning parameter that can trade off the speed of motion and levels of force [5]. The system will become more damped if the wave impedance b increased, and less damped if b decreased [5]. In [4]. their approach to reduce the wave reflections is to match the master and slave impedance. Since then, many researchers proposed augmented wave-variable controllers based on impedance matching to reduce wave reflection and also position drift to achieve stable trajectory tracking. Hongbing and Kenji in [3] proposed a simplified new wave variable architecture as shown in Fig.2.4.

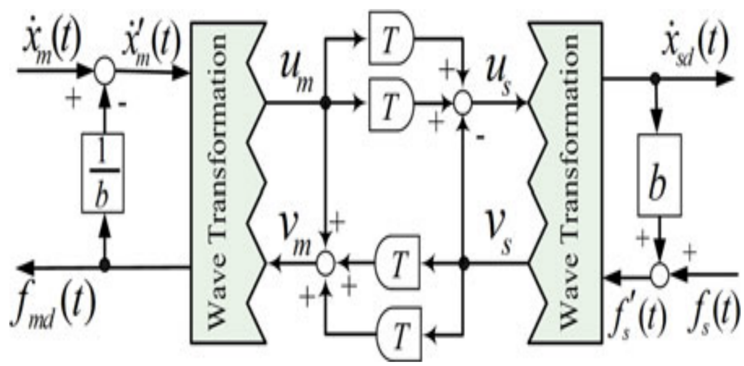


Figure 2.4: Simplifed impedance matching wave architecture, adopted from [3]

The compensation terms of impedance matching can avoid reflections [3], and thus the fluctuation in position tracking is removed [3]. In this augmented architecture, wave variables can be expressed as [3]

$$u_s(t) = 2u_m(t - T) - v_s(t) \tag{2.25}$$

Where u_m and u_s denote the variable u from the master and slave side respectively. [3]

$$v_m(t) = 2v_s(t - T) + u_m(t) \tag{2.26}$$

Where v_m and v_s denote the variable v from the master and slave side respectively. The required additional time delay T can easily be generated by sending the wave inputs in one extra round trip to the slave side and back through the normal communication channel [3].

2.8 Summary

In this chapter, we have analysed the wave variable control approach with constant time delays in communication channel/network. The wave variable control approach can keep the communication channel passive and thus make the system stable with constant time delays. Although wave variable method can guarantee the passivity and stability of the system, the drawbacks of this method are the position drift, and the unavoidable wave reflections due to the limitation of wave architecture [8]. Wave reflection can cause significant oscillation and even make the system unstable [8]. Next, we analysed two approaches to reduce the wave reflection: wave filtering and impedance matching. The wave filtering approach added a low pass filter to reduce the high frequency noise, and the wave impedance matching approach added a compensation term to match the wave impedance. Both methods have significant positive effects on reducing the position drift and wave reflections. After analysing them theoretically in this chapter, next chapter is mainly focused on implementation and simulation based on the analysis of this chapter.

Chapter 3

Simulation Setups and Results

In this chapter, MATLAB/Simulink is used to simulate and verify the wave variable control approach in a two-channel bilateral teleoperation system with constant time delay. First, same constant time delays are applied to the teleoperation system with and without wave variable control to see the advantage of this method. Stability of the system will be checked. Then, in order to reduce position drift, low pass filter (LPF) is added on top of the wave variable control system, how the control parameters affect performance of the wave-variables based bilateral teleoperation system will be discussed.

3.1 Simulation Setups

The simulation run in MATLAB/Simulink R2018b as shown in Fig.3.1 for conventional 2-channel teleoperation system without time delay

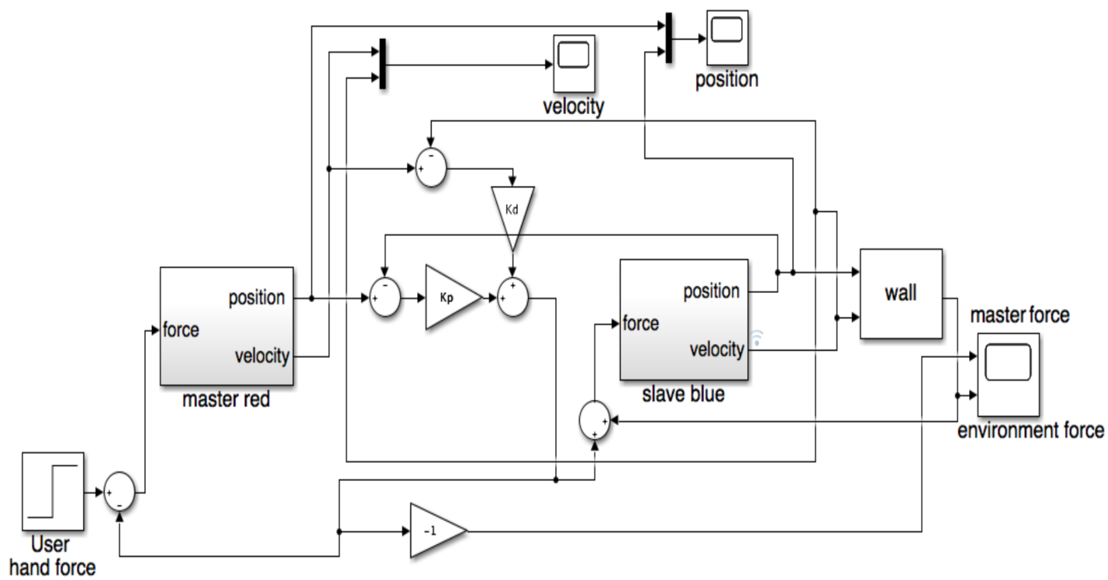


Figure 3.1: Conventional 2-channel Teleoperation System Without Time Delay

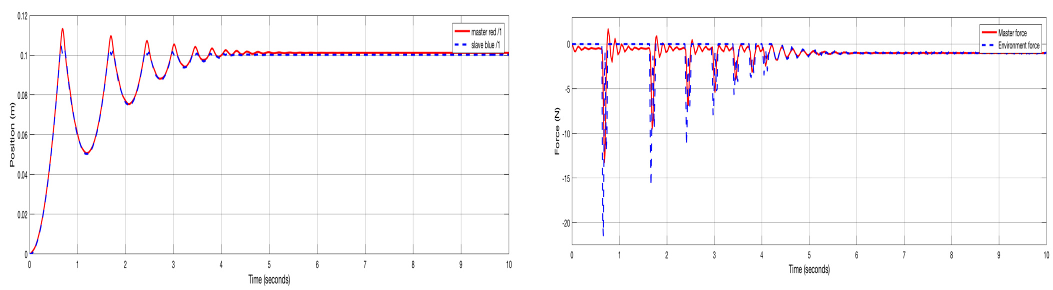
The Simulink models run with sampling period Ts = 10s and 30s. Master and Slave robots are simulated as an one degree of freedom (DOF) mass-damper system with the masses Mm = Ms = 1(kg) and the damping coefficients bm = bs = 0 (Ns/m). For initialization, both Master and Slave robots have initial positions and velocities equal to zeros. For the slave controller, the position gain Kp = 1000 and the velocity gain Kv = 5 for are selected to allow the Slave follows the Master's position and velocity command sent from the Master side. The Slave can make contact with a wall with a stiffness kwall = 5000 (N/m) and a virtual damping coefficient bwall = 5 (Ns/m). There is only inertia in the Master and Slave, and the damping and stiffness are hidden in the slave controller. The wall is placed at an initial position xwall = 0.1 (m). Finally, in the simulation the forward time delay Tf is equal to the backward time delay Tb which equal to the 1-way time delay Td as Tf = Tb = Td.

3.2 Conventional 2-channel teleoperation system Without and With Constant Time Delays

In our simulation, in order to get the simulation results of conventional bilateral teleoperation system without and with constant time delays, the Master robot is pushed with a constant hand force fh = 1 N towards the Virtual Wall. The system is tested without any time delay, then with 3 cases of one-way constant time delays Td = 10, 100ms and 500ms.

From Figure.3.2, it can be seen that the conventional teleoperation system can become stable without any time delay. In Figure 3.2.(a), in free motion the slave position can follow the master position until the slave hit the virtual wall and then the slave is constrained by the virtual environment. It is interesting to note that after the slave position reached to peak value (hit the virtual wall and stop), the master position still increases a bit until reaching to peak value, this is because when the slave stops the master is still moving towards the wall and after a small time delay the master will be constrained by the force reflected back to the master side. Then in constrained motion, the slave bounces back first and the master will follow the slave to move.

In Figure 3.2(b) both the master force and the environment force oscillate in the first 5 seconds, and then reach to steady state at about 1N. Since the user pushed 1N ha nd force to the master, the slave in the environment will also be sensed 1N force, and the force reflected back to the master side finally equals the environment force at 1N. The user is able to sense the force of the virtual environment.

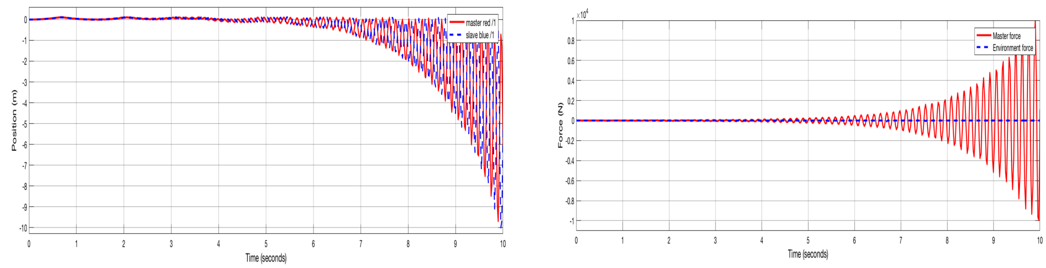


(a) Positions

(b) Forces

Figure 3.2: Conventional 2-channel Teleoperation System Without Time Delays

However, in Figure.3.3 the system become completely unstable even with a small time delay Td = 10 ms. With constant time delays, the force feedbacks from both the master and slave side increase dramatically, oscillate and rise quickly to infinity after the sampling time goes above 10s, without reaching to a steady state. The unstable system is not what we expect in real life applications with teleoperation and should be avoided.



(a) Positions (b) Forces

Figure 3.3: Conventional 2-channel Teleoperation System With Constant Time Delay Td = 10ms

3.3 Wave Variable Approach With Constant Time Delay

In order to make the unstable system become stable with constant time delays, wave variable control is implemented on top of the conventional teleoperation system in Fig.3.4.

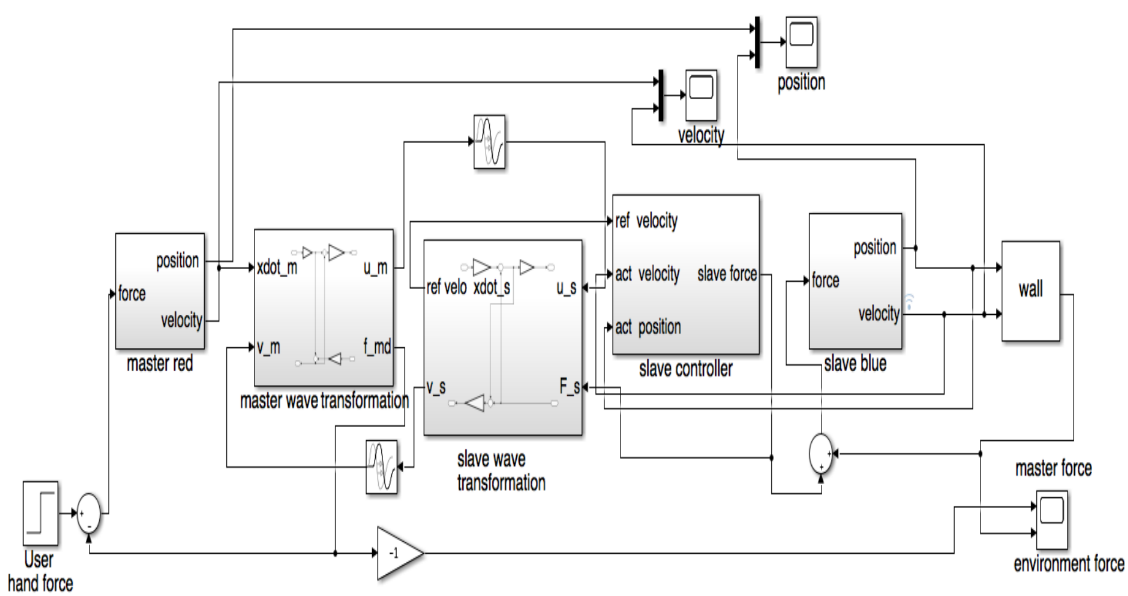
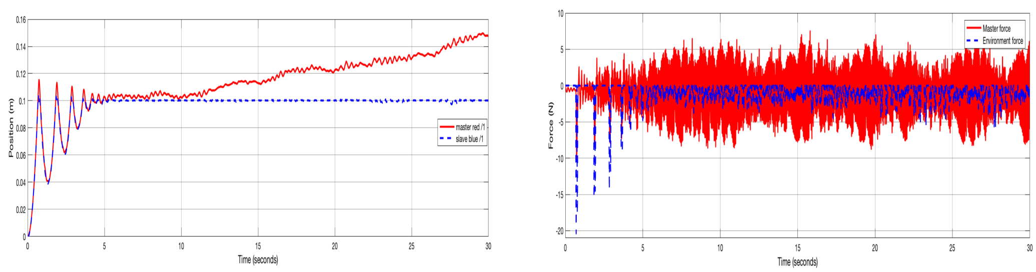


Figure 3.4: Wave Variable Control In 2-channel Teleoperation System With Constant Time Delays

Wave impedance b = 25 and time delay Td = 10ms are selected. It can be seen from Fig.3.5 that the system become stable with wave variable control. However, the steady state error between the master position and slave position becomes larger as the sampling time increase from 10s to 30s. This is position drift caused by numerical errors, and should be avoided. Next section will discuss how to remove the position drift.



(a) Positions (b) Forces

Figure 3.5: Wave Variable Control of Teleoperation System With Constant Time Delays: b = 25, Td = 10ms

3.4 Wave Variable Approach With Low Pass Filter

In order to reduce position drift, a Low Pass Filter (LPF) is added in the forward loop as shown in Fig.3.6.

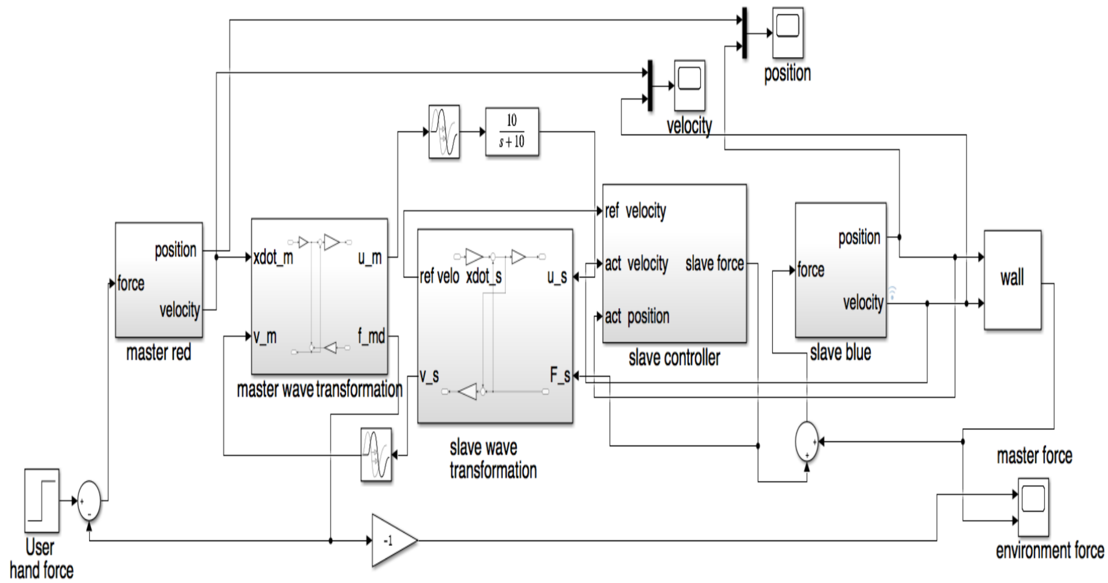
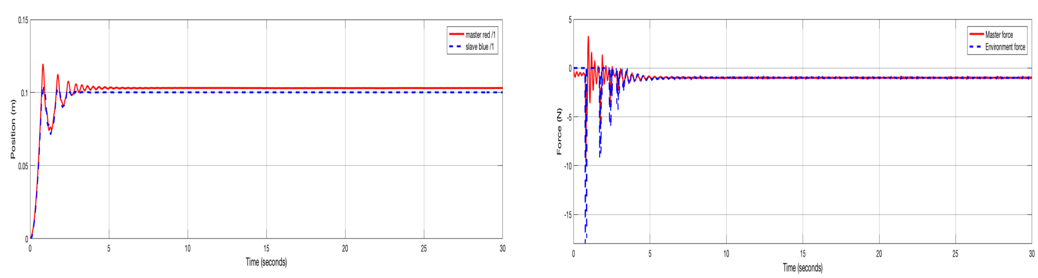


Figure 3.6: Wave variable control with A Forward low pass filter in Teleoperation System With Constant Time Delays

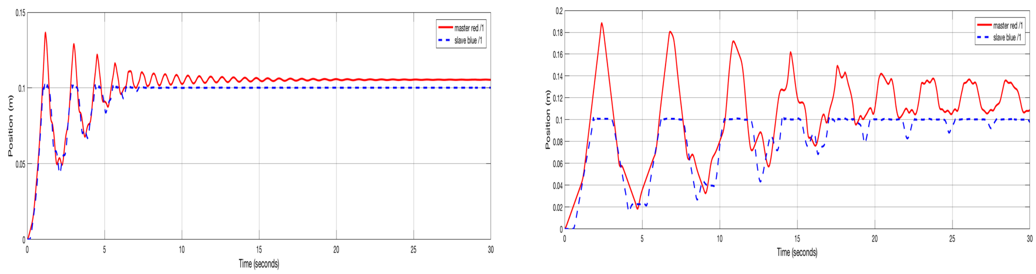
Wave impedance b = 25, cut off frequency $\lambda = 30$ and time delay Td = 10ms are selected for simulation. The simulation results shown in Fig.3.7 illustrate that the position drift has been successfully removed at sampling time 30s under time delay Td = 10ms.



(a) Positions (b) Forces

Figure 3.7: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: b = 25, $\lambda = 30$ and Td = 10ms

However, when the time delay Td increases from 10ms to 100ms, it is interesting to note that in Fig.3.8(a) the steady state error between the master position and the slave position becomes larger. When time delay Td grows to 500ms in Fig.3.8(b), the amplitude of oscillation increases.



(a) Positions: b = 25, $\lambda = 30$ and Td = 100ms (b) Positions: b = 25, $\lambda = 30$ and Td = 500ms

Figure 3.8: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: b = 25, λ = 30, Td = 100ms and 500ms

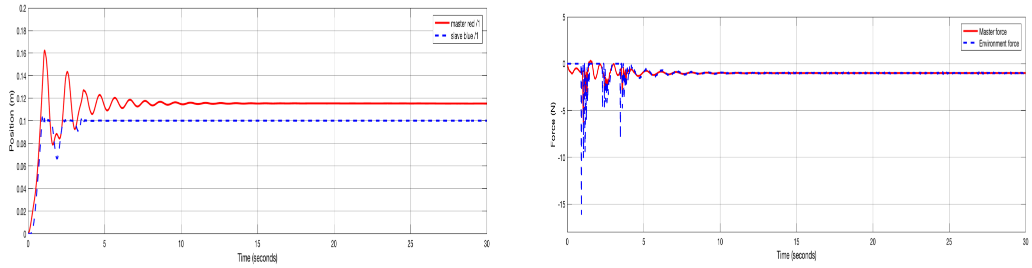
In order to make the performance with larger time delays to behave as close as when Td = 10ms, wave impedance b and cut off frequency λ should be selected properly. Niemeyer and Slotine found the way to select appropriate b and λ is: [5]

$$b \leq m\lambda_{limit} \tag{3.1}$$

when controlling an inertia m, And in practice, the cut off frequency should be selected close to the physical delay: [5]

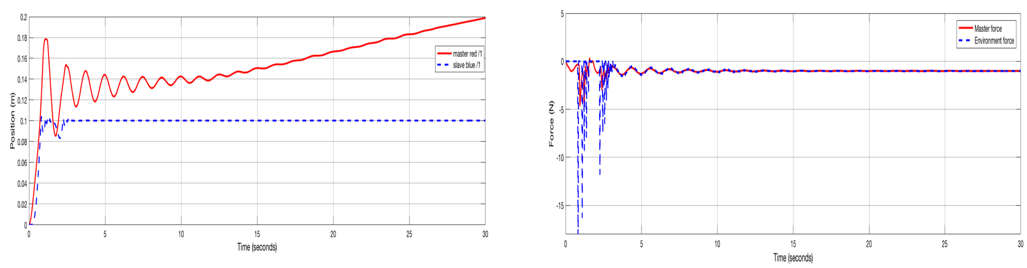
$$\lambda \approx \frac{1}{T} \tag{3.2}$$

Based on these, when Td = 100ms, we calculate $\lambda = 10$ and b = 10 as the benchmark. Then we discuss the effects of control parameters b and λ with time delays Td = 100ms. When discussing the effects of wave impedance b with time delays Td = 100ms, we choose $\lambda_1 = 10$ and $b_1 = 10$ as the benchmark. Then we choose $\lambda_1 = 10$ and $b_2 = 5$, $\lambda_1 = 10$ and $b_3 = 100$ and compare these simulation results with the benchmark, the simulation results are displayed in Fig.3.9-3.11.



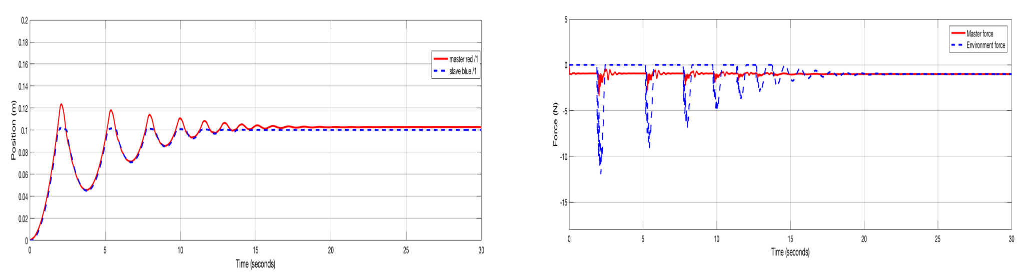
(a) Positions: $b_1 = 10$, $\lambda_1 = 10$, Td = 100ms (b) Forces: $b_1 = 10$, $\lambda_1 = 10$, Td = 100ms

Figure 3.9: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_1 = 10$, $\lambda_1 = 10$, Td = 100ms



(a) Positions: $b_2 = 5$, $\lambda_1 = 10$, Td = 100ms (b) Forces: $b_2 = 5$, $\lambda_1 = 10$, Td = 100ms

Figure 3.10: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_2 = 5$, $\lambda_1 = 10$, Td = 100ms



(a) Positions: $b_3 = 100$, $\lambda_1 = 10$, Td = 100ms (b) Forces: $b_3 = 100$, $\lambda_1 = 10$, Td = 100ms

Figure 3.11: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_3 = 100$, $\lambda_1 = 10$, Td = 100ms

Based on these 3 cases of b = 5,10,100, we can see that when the wave impedance b increases:

1. The steady state error between the master position and the slave position decreases.

2. The slave settling time Tss becomes longer, ideally we want to make the slave to settle down as quickly as possible.

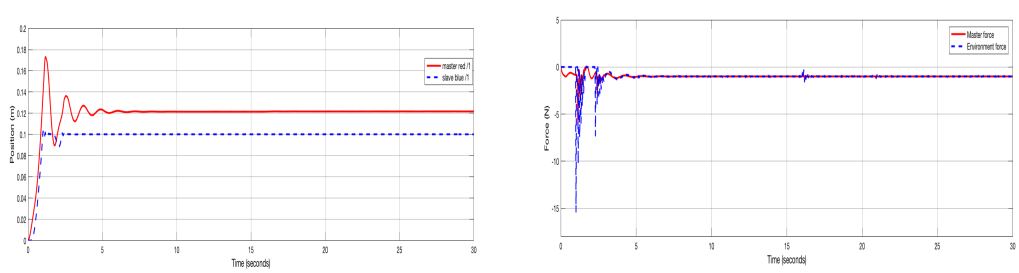
3. The master oscillation when the slave settled down becomes smaller. When the slave settled down, the master still oscillate, the faster the master stops, the better the performance is.

4. The time for the master oscillation to settle down is the shortest when b = 10, when b = 5 and 100 the master takes longer time to settle down.

5. The forces figure show the user actually feels the forces applied to the master. When the slave makes contact with the wall, the master follows the slave shows how good the environment feels the user.

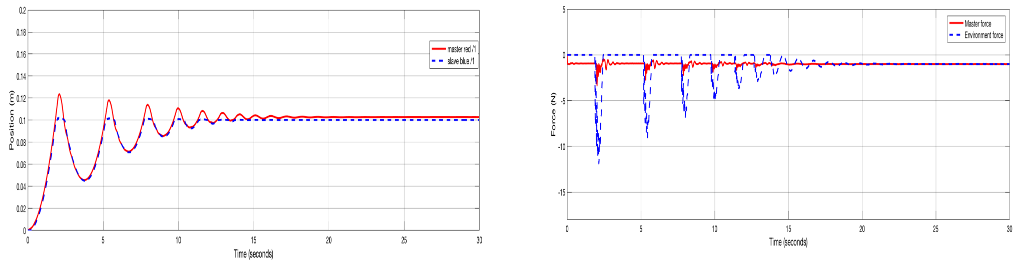
Based on the above simulation results, we can conclude that when the wave impedance b increases, the performance is improved if we care more about the steady state error rather than the slave settling time. if we care more about the slave settling time rather than the steady state error, we may say when the wave impedance b increases, the performance is degraded.

Then in order to discuss the effects of cut off frequency λ with time delays Td = 100ms, we still choose λ_1 = 10 and b_1 = 10 as the benchmark, and compare its simulation results with λ_2 = 5 and b_1 = 10, λ_3 = 25 and b_1 = 10. The simulation results are shown in Fig.3.12-3.13.



(a) Positions: $b_1 = 10$, $\lambda_2 = 5$, Td = 100ms (b) Forces: $b_1 = 10$, $\lambda_2 = 5$, Td = 100ms

Figure 3.12: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_1 = 10$, $\lambda_2 = 5$, Td = 100ms



(a) Positions: $b_1 = 10$, $\lambda_3 = 25$, Td = 100ms (b) Forces: $b_1 = 10$, $\lambda_3 = 25$, Td = 100ms

Figure 3.13: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_1 = 10$, $\lambda_3 = 25$, Td = 100ms

Based on these 3 cases of λ = 5,10,25, we can see that when the cut off frequency λ increases:

1. The steady state error between the master position and the slave position decreases.

2. The slave settling time Tss becomes longer, ideally we want to make the slave to settle down as quickly as possible.

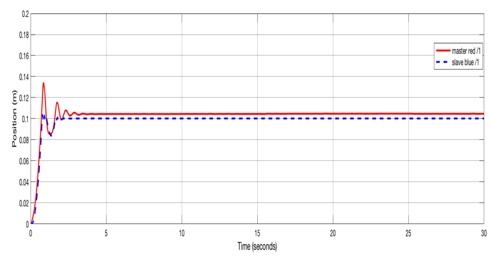
3. The master oscillation when the slave settled down becomes larger. When the slave settled down, the master still oscillate, the faster the master stops, the better the performance is.

4. The time for the master oscillation to settle down increases.

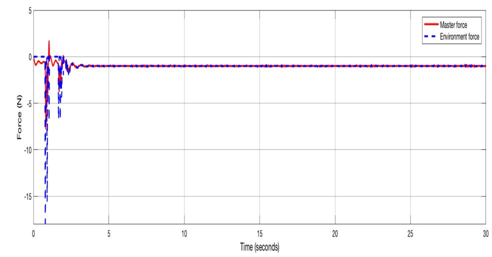
5. The forces figure show the user actually feels the forces applied to the master. When the slave makes contact with the wall, the master follows the slave shows how good the environment feels the user.

Based on the above simulation results, we can conclude that when the cut off frequency λ increases, the performance is degraded.

Next, in order to discuss the effects of time delays Td, we still choose λ_1 = 10, b_1 = 10 and Td_1 = 100ms as the benchmark, and compare its simulation results with λ_1 = 10, b_1 = 10, Td_2 = 10ms, and λ_1 = 10, b_1 = 10, Td_3 = 500ms . The simulation results are shown in Fig.3.14-3.15.

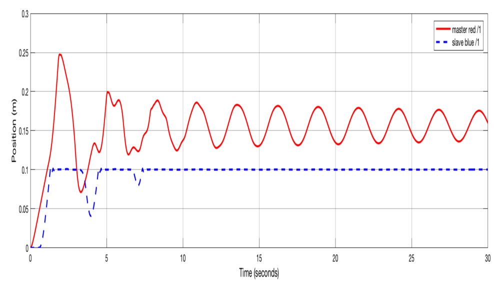


(a) Positions: $b_1 = 10$, $\lambda_1 = 10$, $Td_2 = 10$ms

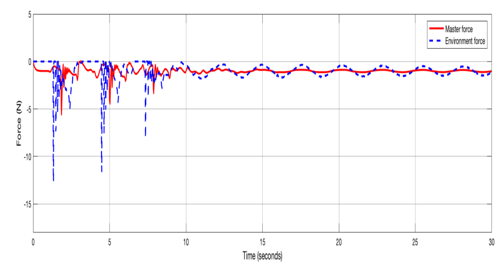


(b) Forces: $b_1 = 10$, $\lambda_2 = 10$, $Td_2 = 10$ms

Figure 3.14: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_1 = 10$, $\lambda_1 = 10$, $Td_2 = 10$ms



(a) Positions: $b_1 = 10$, $\lambda_1 = 10$, $Td_3 = 500$ms



(b) Forces: $b_1 = 10$, $\lambda_1 = 10$, $Td_3 = 500$ms

Figure 3.15: Simulation Results for Wave Variable Control With Low Pass Filter of Teleoperation System with Constant Time Delays: $b_1 = 10$, $\lambda_1 = 10$, $Td_3 = 500$ms

Based on these 3 cases of Td = 10,100,500ms, we can see that when the time delay Td increases:

1. The steady state error between the master position and the slave position becomes larger.

2. The slave settling time Tss becomes longer, ideally we want to make the slave to settle down as quickly as possible.

3. The master oscillation when the slave settled down becomes larger. When the slave settled down, the master still oscillate, the faster the master stops, the better the performance is.

4. The time for the master to settle down becomes longer.

5. The forces figure show the user actually feels the forces applied to the master. When the slave makes contact with the wall, the master follows the slave shows how good the environment feels the user.

Based on the above simulation results, we can conclude that when the time delay Td increases, the performance is degraded.

Chapter 4

Conclusions

4.1 Conclusion

With the advance of technology, teleoperation has a promising aspect in many areas, such as space exploration, undersea detection and remote telesurgery. It can be imagined that one day, after the teleoperation technology and remote telesurgery become mature, it can replace traditional manual surgery and significantly improve the efficiency and saving more lives. However, in the communication channel, the inner time delays always make the bilateral teleoperation system unstable unavoidably. One of an effective solution to deal with this issue is the wave variable control approach. This project intend to concentrate on investigating and evaluating the 2-channel bilateral teleoperation with wave variabale control under constant communication delays. From the simulation results, we can see that the wave varibale control method is able to keep the system passive and thus stable with constant time delays. Although wave variable control can guarantee the passivity of the system, since it is a conservative approach which pursue the excessive passivity, it has some shortcomings such as wave reflection and position drift. In simulation results in Chapter 3, we can see with large time delays Td = 100ms, there is position drift. To reduce the position shift, a Low Pass Filter (LPF) added on top of the conventional teleoperation system, which proved to be an effective and efficient way to reduce the position drift. However, the control parameters wave impedance and cut-off frequency should be chosen carefully to avoid unwanted system behaviors as discussed in Sec 3.4. The advantages and disadvantages of wave variable control approach with constant communication time delays is summarized as following:

Advantages:

1. Simple and straightforward, easy to implement.
2. Fast, simple computation work to drive mathematical model.
3. Guarantee the passivity and thus the stability of the system.
4. Handle linear and nonlinear system.

Disadvantages:

1. Wave reflection.
2. Position drift.
3. Extreme conservative approach, so sacrifice transparency to some extent.
4. Can handle constant time delays but cannot cope with time varying delays.

4.2 Future Works

For the limitations in this report, since the time delays in communication channel and our mass-spring-damper simulation model are simulated by MATLAB/Simulink, we cannot fully evaluate the performace of wave variable control approach in real life applications such as remote telesurgery, undersea detection and space exploration tasks. To facilitate simulation, the conditions in simulation is ideal for example we assume no friction when pushing the ball to the wall in the mass-damper system model. However, in real life ideal condition and environment is impossible and external disturbances should be taken into account. Therefore, the future work is suggested to implement the wave variable control approach in real life situations and applications, to help us have a better understanding of this control method.

Bibliography

[1] Peter F Hokayem and Mark W Spong. Bilateral teleoperation: An historical survey. *Automatica*, 42(12):2035–2057, 2006.

[2] Dale A Lawrence. Stability and transparency in bilateral teleoperation. *IEEE transactions on robotics and automation*, 9(5):624–637, 1993.

[3] Hongbing Li and Kenji Kawashima. Achieving stable tracking in wave-variable-based teleoperation. *IEEE/ASME Transactions on Mechatronics*, 19(5):1574–1582, 2013.

[4] Günter Niemeyer and J-JE Slotine. Stable adaptive teleoperation. *IEEE Journal of oceanic engineering*, 16(1):152–162, 1991.

[5] Günter Niemeyer and J-JE Slotine. Using wave variables for system analysis and robot control. In *Proceedings of International Conference on Robotics and Automation*, volume 2, pages 1619–1625. IEEE, 1997.

[6] Roberto Oboe and Paolo Fiorini. A design and control environment for internet-based telerobotics. *The International journal of robotics research*, 17(4):433–449, 1998.

[7] Altan Odabasioglu, Mustafa Celik, and Lawrence T Pileggi. Prima: Passive reduced-order interconnect macromodeling algorithm. *IEEE Transactions on computer-aided design of integrated circuits and systems*, 17(8):645–654, 1998.

[8] Da Sun, Fazel Naghdy, and Haiping Du. Application of wave-variable control to bilateral teleoperation systems: A survey. *Annual Reviews in Control*, 38(1):12–31, 2014.

[9] Neal A Tanner and Günter Niemeyer. Improving perception in time-delayed telerobotics. *The International Journal of Robotics Research*, 24(8):631–644, 2005.

[10] Neal A Tanner and Günter Niemeyer. High-frequency acceleration feedback in wave variable telerobotics. *IEEE/ASME Transactions on Mechatronics*, 11(2):119–127, 2006.

[11] Yongqiang Ye and Peter X Liu. Improving trajectory tracking in wave-variable-based teleoperation. *IEEE/ASME Transactions on Mechatronics*, 15(2):321–326, 2009.

[12] Min Zheng, Qing-Hai Chen, Wei Xiao, and Hai-Nan Yang. Bilateral teleoperation with reducing wave-based reflections. *Advances in Manufacturing*, 1(3):288–292, 2013.