Matched Impedance Control for Bilateral Teleoperation

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***Abstract*—The contribution of control theories to the field of teleoperation in robotics have made possible to execute tasks and manipulate objects remotely as though physically present through master and slave robotic devices. This capability is enhanced by the ability to perceive the remote environment and the forces resulting from the slave device's interaction with it. Control strategies have advanced towards incorporating this enhancement in order to improve the performance of teleoperation systems and widen the areas of application. Teleoperation has proven effective in circumstances where the environment to be explored is hazardous to man or inaccessible. The extended potentials of enhancing human abilities in various fields through teleoperation have been beset with the challenges of stability and transparency since inception. These challenges stem from the distance between the local and remote environments often involved in teleoperation and the ensuing delay in transfer of information signals or constrain in transferring data. A range of control schemes and structures have been projected to overcome the challenge of stability based on the concept of passivity. This research employs Proportional-Derivative and Proportional-Integral controllers for position and velocity control. It introduces a modification to the generic approach to matching impedance control in order to enhance performance by eliminating interdependent variable computations and preventing algebraic loops. This improved matching impedance control approach is implemented exploiting the passivity theory using the wave variable formulation in simulation.**

Performance of the control approach is analysed over varied values of the system and controller variables and the resulting changes in response specifications discussed. The scattering operator is found to enhance master-slave joint angle tracking though requiring large actuation force.

Keywords—component; Matched Impedance, Teleoperation, Proportional-Derivative (PD), Proportional-Integral (PI), Telepresence, Unilateral teleoperation, Bilateral teleoperation

1. INTRODUCTION

A robot is a machine designed with computer programs to perform human tasks faster with high level of accuracy than humans [1]. The operation of a robot is aimed at reduced time and increased efficiency in various industries such as medicine and services and also in hazardous working environment where human safety is at risk. Teleoperation over the years, has provided an effective means of controlling robots, effectively bridging the complexity of robot-driven tasks with human intuition. A teleoperator is a double robot system wherein a remote slave robot mimics the motion of a master robot directed by a human operator in a local environment [2]. Consequently, master and slave devices are often referred to as teleoperators and deemed to include all or several of communication channels interfacing the human operator, artificial sensors, upper limbs and a vehicle for carrying these. Hence, teleoperation entails direct and sustained human control of the teleoperators. Telepresence is a significant attribute usually associated with the field and is an ideal condition of acquiring and effectively communicating to the human operator, sufficient information about the teleoperator and remote task environment to enable natural sensing. Hence, build an impression of being physically present at the remote location. A human operator is required in teleoperation for periodic stipulation of objectives, constraints, plans and orders and adapting these based on reflected information regarding accomplishments, difficulties from the slave device in the remote environment. Teleoperation is also referred to as telemanipulation indicating the capability of remote handling and operation and has found applications in several fields including nuclear research and industry, space, underwater, mining, medicine and in most cases tasks in hazardous or inaccessible environments [3][4]. This is because the telemanipulation technique allows human capability to carry out work remotely as though by hand in circumstances where direct action is infeasible or unsafe. A human operator is vital due to unpredictability and a consequent impossibility to establish models for operations before hand. If the master motion and force are transmitted to the slave site without resulting reflection to the master site from the slave site, the teleoperation system is termed unilateral. The provision of contact force information from the remote environment to the human operator can improve the task performance and is more useful when the measured force is directly reflected to the motors on the master [5][6][7]. This denotes realization of an ideal situation of direct action of the human operator on the remote environment unlike a lack of force feedback encountered in unilateral teleoperation as illustrated in Figure 1.

The reflection of the contact force to the human operator through the master manipulator indicates bilateral control of the teleoperator and is shown in Figure 2. The communication between local and remote environments often involves large distances and may impose limited data transfer. This can result in substantial time delays and may affect the overall stability of the teleoperation system.

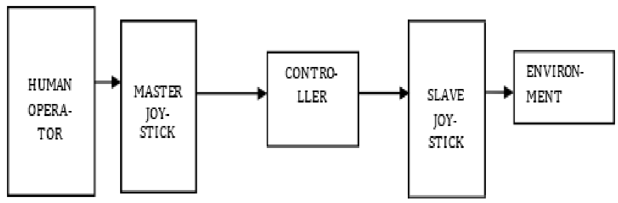

Figure 1: Layout of Unilateral Teleoperation

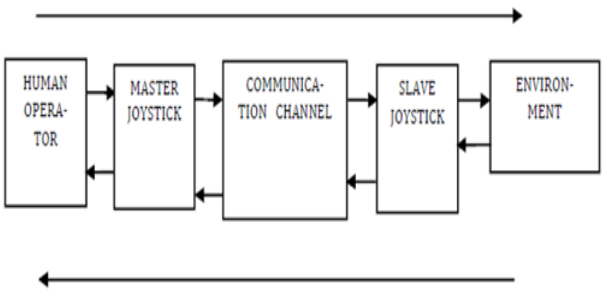

Figure 2: Layout of Bilateral Teleoperation

A teleoperation system typically comprises a human operator in a local environment actuating a master connected by means of a communication channel to a slave device interacting with a remote environment. It is introduced when human maneuver is required due to unpredictability and a consequent impossibility to create models for the entire operation. Communication between local and remote environments is often associated with long distances and limited data transfer hence a communication time delay [8][9][10] is experienced in the transmitted and reflected interaction causing instability in the force-reflecting teleoperation system [10]. Control designs have been proposed to take care of this problem of communication time delay formed on different techniques including passivity, predictive, adaptive and compliance control among others. Prominent among them is the passivity-based control technique which exploits the basic property of passivity of teleoperators. The passivity-based approach brought about stable time delayed bilateral teleoperation [8] as a consequence of mimicking concepts depicted in physical systems and accordingly providing energy conservation and stability assurance. The passivity-based reasoning facilitates the disengagement of the teleoperation system enabling the isolation of the communication channel component and specifies how instability sets in due to time delay [11]. As a result of this breakthrough, earlier delayed results in the field of teleoperation were adapted to the new context of passivity.

The aim of this paper is to address the problem of controlling bilateral teleoperation systems in the presence of fixed time delays by designing and implementing a matched impedance passivity-based controller and investigating the performance specifications with variation of the system and controller parameters.

2.0 METHODOLOGY

The diverse advancements in the field of teleoperation hinge on certain landmark theories which answer key questions in stability considerations, performance and robustness by imitating concepts inherent in physical systems. A wide range of improvement has since been attained in the complexity of teleoperation systems controlled bilaterally, preservation of desired performance in the preservation presence of fixed and varying time delays and a variation in the control structures available for implementation. The significant attribute of two-port networks, passivity theory and wave scattering discussed in this section have retained their relevance in the advent of contemporary approaches like neural networks-based control, virtual model based control, sliding mode control, gain scheduling control, adaptive control, predictive control, virtual reality technology and others.

2.1 Passivity Theory

Passivity is an input-output property of dynamical systems derived from network theory primarily concerned with energy exchange between interconnected systems. It corresponds to a mathematical depiction of the intrinsic physical concepts of energy and power [12]. Applying the passivity theory allows for the interconnection of systems and still retains global stability property. A system can be considered passive if it obeys the condition;

$$P_{in} = X^T y = \frac{dE}{dt} + P_{diss} \quad (1)$$

Denoting the parameters thus:

'Pin' as the input power to the system and a scalar product of the system's input and output vectors 'X' and 'Y'.

'E' as the lower bound energy storage function of the system. 'P_{diss}' as the system's non-negative power dissipation function.

This indicates that the total energy supplied by the system does not exceed its initial stored energy until a time 't' when negative energy is transferred into the system.

2.2 Scattering Transformation

The scattering transformation is well known in transmission line theory and was adopted by Anderson and Spong [12] in the field of bilateral teleoperation to attain passivity of the teleoperation system. The bilateral teleoperation is considered as a series cascade of one and two port networks with a transfer of force and velocity in mechanical systems or voltage and current in electrical systems notation. Considering the mechanical system representation of the two-port network as shown in Figure 4 and a mechanical teleoperation system arrangement as in Figure 5, the relationship between this force and velocity at the system's ports symbolize the hybrid matrix which is used in defining the scattering operator 'S'.

The scattering operator is obtained from the relation;

$$F - v = S(F + v) \quad (2)$$

Also the scattering operator can be specified in frequency domain as a scattering matrix S(s) from the relation:

$$F(s) - v(s) = S(s)\big(F(s) + v(s)\big) \quad (3)$$

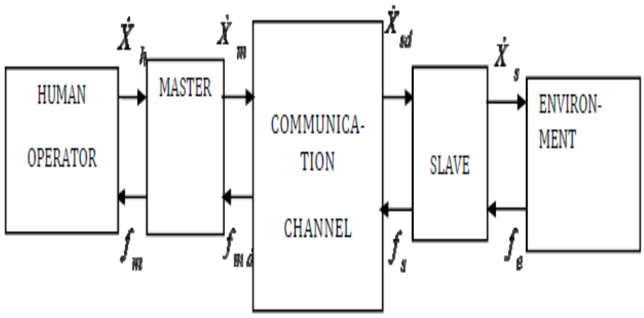

Figure 3: Conceptual Block Diagram of Teleoperation System with Mechanical Arrangement.

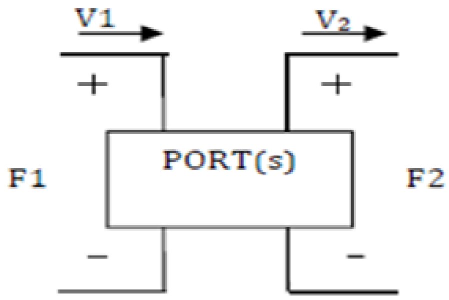

Figure 4: A Two Port Ideal Transformer

2.3 Wave Variable Formation

The wave variable formation is akin to the scattering transformation and conceptually related to the passivity theory [13]. This can be seen in the exchange of wave variables Um and Us as reference signals in place of power variables $\dot{X}m$ and fs shown in Figure 4. Equation 4 shows the total power flow within the communication channel.

$$Um(t) = \frac{1}{\sqrt{2b}}\big(fmd(t)\big) + b\dot{x}m(t)$$

$$Us(t) = \frac{1}{\sqrt{2b}}\big(fs(t) + b\dot{x}s(t)\big) \quad (4)$$

Where $\dot{\boldsymbol{X}}\boldsymbol{sd}$ and $\boldsymbol{fmd}$ are the received power signals at the slave and master side respectively. In comparison with the scattering transformation, $\boldsymbol{b}$ is the characteristic impedance.

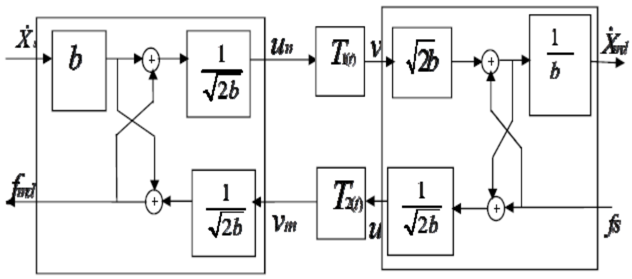

Figure 5: Wave Variable Formation

2.4 Impedance Matching

The concept of impedance matching introduced by Niemeyer and Slotine [13] prevents the occurrence of wave reflections which degrades performance in bilateral teleoperation systems. Wave reflections are known to occur in physical systems where the wave carrier's impedance changes. The adaptation of the communication channel to guarantee passivity with time delays by the wave variable formation may result in reflections at master and slave sites. Wave reflections in bilateral teleoperation may cause distortion of information and oscillatory behavior. Thus, impedance matching termination elements are introduced at each end of the communication channel [14][15] as shown in Figure 6 or control parameters chosen precisely to match the impedance of the wave transmission to the remaining system [11].

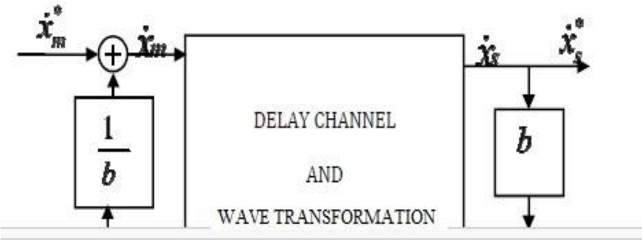

Figure 6: impedance matching

2.5 Discretion of the Joystick

The experimental device used is a pair of PHANTOM Omni haptic joysticks. As shown in Figure 7 (a) and (b), it is a six (6) degree of freedom (DOF) haptic device designed by Sensable Technologies for virtual manipulations and remote handling with three actuated joints and three non-actuated joints respectively. For kinematic symmetry an identical pair of the Phantom OMNI device is used with a single degree of freedom considered for implementing matching impedance control of the bilateral teleoperation.

Figure 7: PHANTOM Omni Showing Actuated and Non-Actuated Joints [34]

A robot is commonly structured to allow coordinated displacement in one or more of its joints and so requires definition of reference frames. The relationship between a given link and its neighbouring links is essential in the allocation of reference frames. A reference frame defines the orientation of each joint and so may differ for each joint. It is uniquely identified by its position and orientation when compared to the origin (the robot's base frame). The complexities arising from several rotation and displacement configurations with different reference frames is avoided by adopting homogenous transformations which map frames one to another by means of a homogenous transformation matrix [16]. The general form of this homogenous transformation matrix is:

$$T = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} n_x & s_x & a_x & dx \\ n_y & s_y & a_y & dy \\ n_z & s_z & a_z & dz \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and}$$

$$Rotation\ (R) = \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix},$$

$$Displacement\ (d) = \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} \qquad (5)$$

2.6 Forward Kinematics

Denavit-Hartzenberg (D-H) representation is a common convention in kinematic analysis comprising four unique parameters that identify any given link [12]. The nature of a joint determines the definitions of its displacement, hence revolute joints undergo angular displacement and prismatic joints link displacement. Using the D-H convention to formulate the homogenous matrix allows appropriate representation of specific links in relation to neighboring joints and links as follows:

$$A_k = \begin{bmatrix} \cos(\theta k) & -\sin(\theta k) & 0 & 0 \\ \sin(\theta k) & \cos(\theta k) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & dk \\ 0 & 0 & 0 & 1 \end{bmatrix} \times$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta k) & -\sin(\theta k) & 0 \\ 0 & \sin(\theta k) & \cos(\theta k) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

2.7 Inverse Kinematics

Inverse kinematics is essential for trajectory decomposition and computation of associated joint angles to achieve the end-effectors desired pose. Physical joint angle limits and restrictions in design often yield unique solutions. When only a set of possible joint angles exist to reach the desired end-effector pose, unique solutions are also obtained. In the PHANTOM Omni, inbuilt mechanical stops restrict the possible joint angle that can be obtained and exceeding these stops may damage the device.

2.8 Velocity Kinematics

Velocity kinematics involves the derivation of these joint to end-effector relationships and it is of significance since a robot's position and speed in reference to its desired trajectory is crucial to task execution [14]. The time differentiation of the forward kinematics equations yields the velocity kinematics. The forward kinematics relationship is given by;

$$x = f(q) \qquad (7)$$

Differentiating to obtain the velocity kinematics yields;

$$\frac{dx}{dt} = \frac{df\ (q)}{dt}\frac{dq}{dt} \qquad (8)$$

$$\dot{x} = J(q)\dot{q} \qquad (9)$$

Where J is the jacobian of the robot and a nonlinear function of the joint position q and $\dot{q}$ is the joint velocities.

2.9 The Quanser System

The Quanser system comprises the entire experimental setup which includes the phantom OMNI pair and the QUARC software. The PHANTOM Omni receives joint velocity or torque input signals in joint space or Cartesian space and is capable of giving outputs of its encoder values, position, joint and gimbal angle values. It has a velocity limit of 1200 mm/s [17].

2.10 The Quarc

The QUARC software provides the virtual environment through which the hardware and software interact. It also allows configuration of the Phantom OMNI's for master and slave operations respectively to ease distinction and for proper signal and command management. The modelling, input signal specification, controller design and performance analysis is carried out in MATLAB Simulink environment.

2.11 Unilateral Teleoperation

Unilateral teleoperation indicates a teleoperation system where only the master's motion and force is transmitted to the slave device [10]. Position or velocity information specified by the human operator through actuation of the master device is transferred to the slave device without a feedback of the resulting force imposed on the slave device. To achieve set point tracking and guarantee stability, the slave device compares its output with the master's reference signal and performs adequate compensation by means of a closed loop feedback position controller. Because there is no feedback interconnection between the master and the slave devices, time delay during transfer of information does not degrade system performance or compromise stability.

2.12 Experimentation of Unilateral Teleoperation

A human operator varies the position of the master joystick thereby specifying a trajectory as a reference input to the slave device. By appropriate use of proportional-derivative (PD) control action, the slave device tracks the trajectory of the master having compensating all deviations detected between both the slave and the master. However, the exertion of external force on the slave from interactions within its environment is not perceived by the master due to the lack of a feedback interconnection. A single degree of freedom was assumed for experimentation while the two remaining actuated joints were assigned fixed inputs to enable ease of motion about the base revolute joint which was being considered.

2.13 Experimentation of Bilateral Teleoperation

The bilateral teleoperation conceptual block diagram and layout is shown in Figure 8 (a) and (b) respectively.

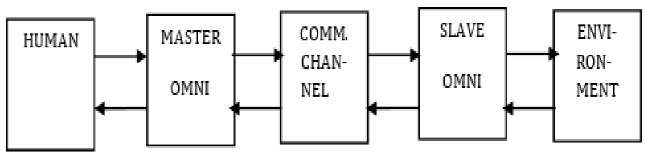

Figure 8(a): Conceptual Block Diagram of Bilateral Teleoperation

By moving the master Omni, a human operator varies the position of the master joystick specifying a reference input to the slave device. Employing proportional- integral (PI) control action, the slave device is able to track the position of the master. In bilateral teleoperation either of the devices can serve as the master or slave. This means that if the PHANTOM Omni configured as the slave is actuated to specify a reference input, the master device mimics its position. Because force is reflected to the master Omni, if an obstacle is encountered by the slave in the remote environment, the master promptly perceives this by the force reflection to its motors. This enables the initiating of a corrected motion by the human operator.

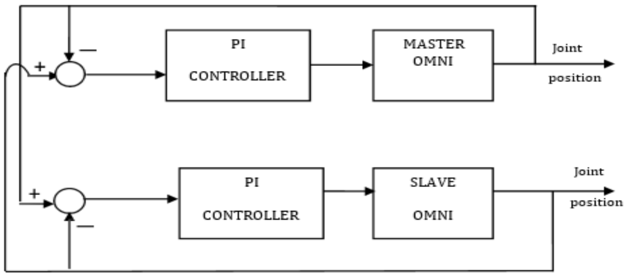

Figure 8(b): Unilateral Teleoperation with PI Controller

2.14 Matching Impedance Controlled Teleoperation

Following Gunter Niememyer et al. [13], the matching impedance control strategy is targeted at solving the problem of instability in bilateral teleoperation systems due to time delay. Utilizing the wave variable formation of the scattering theory, mathematical computations are carried out to calculate the force and wave variables transmitted over the components of the system as shown in Figure 9.

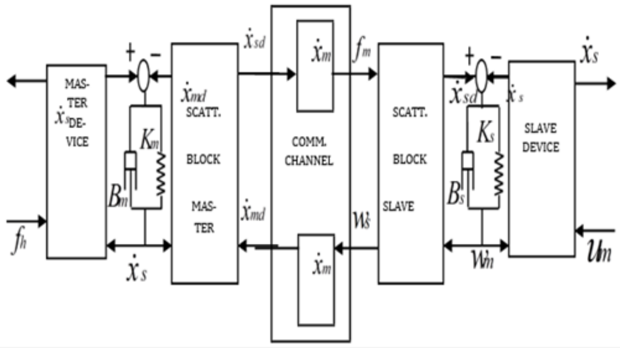

Figure 9: Matching Impedance Teleoperation Layout

$\dot{x}k$and fk represent interchanged power variables with $k \in \{h, m, s, e\}$ and the sub index d indicates delayed variables. *um*, *us* , *ws* and *wm* are the wave variables resulting from the scattering transformation of the power variables. Km, Bm, Ks and Bs are the master and slave impedance controller parameters represented as the parallel of a spring Km, Ks and a $damper$ Bm, Bs . From the wave variable formation, we have that;

$$\begin{pmatrix} um \\ \dot{x}md \end{pmatrix} = \begin{pmatrix} \sqrt{2}B^{\frac{-1}{2}} & -I \\ B^{-1} & -\sqrt{2}B^{\frac{-1}{2}} \end{pmatrix} \begin{pmatrix} fm \\ wm \end{pmatrix} \qquad (10)$$

$$\begin{pmatrix} ws \\ \dot{x}sd \end{pmatrix} = \begin{pmatrix} \sqrt{2}B^{\frac{-1}{2}} & -I \\ -B^{-1} & \sqrt{2}B^{\frac{-1}{2}} \end{pmatrix} \begin{pmatrix} fs \\ ws \end{pmatrix} \qquad (11)$$

Where the B > 0 is the line impedance.

It can be seen that the transmitted variables are the wave variables;

$$us(t) = um(t - \Delta T), wm(t) = ws(t - \Delta T) \qquad (12)$$

Where $\Delta T \geq 0$ is the communication delay and is taken to be constant. This configuration typifies a lossless system in relation to the storage (Hamiltonian) function which indicates the integral of the power of waves for the duration of the transmission by the relation;

$$Hc(t) = \frac{1}{2}\int_{t-\Delta T}^{t}(\|um(\tau)\|^2 + \|ws(\tau)\|^2)d\tau \qquad (13)$$

It follows that,

$$-f_s^1(t)\dot{x}sd(t) + f_m^1(t)\dot{x}md(t) = Hc(t) \qquad (14)$$

This holds for all ΔT and regardless of its actual value, passivity is maintained. Since the interconnection of passive subsystems results in a system that is passive, therefore a stable system is guaranteed.

As mentioned earlier, the occurrence of wave reflections due to termination at an impedance different from the line impedance is addressed by the inclusion of damping terms on master and slave sides or specified conditions in choice of impedance controller parameters termed impedance matching [11]. This accounts for the use of symmetric impedance controllers at each end of the communication channel enabling reception of force information and provision of **velocity signals. From figure 8, the equations of the impedance controllers can be written as;**

$$fm = Km\int(\dot{x}m - \dot{x}md)dt + Bm(\dot{x}m - \dot{x}md) \qquad (15)$$

$$fs = Ks\int(\dot{x}sd - \dot{x}s)dt + Bs(\dot{x}sd - \dot{x}s) \qquad (16)$$

These impedance controllers are two PI controllers with transfer functions:

$$fm = \left(\frac{km}{s} + Bm\right)em \text{ where } em = \dot{x}m - \dot{x}md \qquad (17)$$

$$fs = \left(\frac{ks}{s} + Bs\right)es \text{ where } es = \dot{x}sd - \dot{x}s \qquad (18)$$

By this, energy is not only being transmitted through the springs Km and Ks but dissipated partly in the dampers Bm and Bs . Because of this, artificial damping is required to guarantee passivity when there is interaction with the environment. The controller parameters Km and Ks are the stiffness constants of the springs while Bm and Bs are the viscous frictions. Selecting Bm and Bs equal to the scattering operator B averts the occurrence of wave reflections [13]. From equations (10) and (11), an interdependence can be seen in the computation of $\dot{x}md$ and fm as well as $\dot{x}sd$ and fs resulting in an algebraic loop. In this design, an alternative approach is devised by the merging of the PI controller and the scattering block on the master and slave sides as shown in Figure 9. Following Gunter Niemeyer [18], the controller equations for this modified teleoperation structure using the equivalent wave variables formation of the scattering theory from equations (10) to (18) was derived.

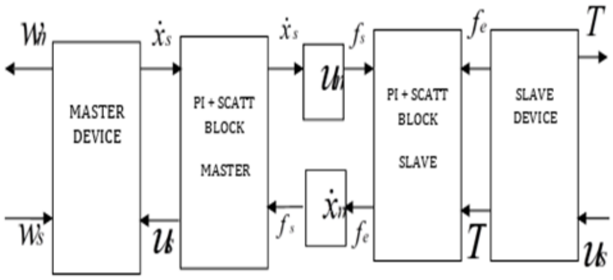

Figure 10: Matching Impedance Teleoperation System; Modified To Eliminate Algebraic Loop [18].

For the PI + scattering block of the Master Omni:

$$fm = \left(\frac{Km + Bms}{\left(\frac{Bm}{B+1}\right)s + \frac{Km}{B}}\right)\dot{x}m + \sqrt{\frac{2}{B}}\left(\frac{Km + Bms}{\left(\frac{Bm}{B+1}\right)s + \frac{Km}{B}}\right)wm$$

Also, for the PI + scattering block of the slave Omni:

$$fs = \left(\frac{Ks + Bss}{\left(\frac{Bs}{B+1}\right)s + \frac{Ks}{B}}\right)\dot{x}s + \sqrt{\frac{2}{B}}\left(\frac{Ks + Bss}{\left(\frac{Bs}{B+1}\right)s + \frac{Ks}{B}}\right)ws$$

The wave variables are derived from equation (10) as follows;

$$um = fm \times \sqrt{2}B^{\frac{-1}{2}} - I \times wm \qquad (19)$$

$$ws = fs \times \sqrt{2}B^{\frac{-1}{2}} - I \times us \qquad (20)$$

The above controller equations and wave variable equivalents are implemented directly in MATLAB Simulink block diagram programming.

By assuming simple first order transfer functions for the Master and Slave Omni's, the matching impedance bilateral teleoperation system is implemented in simulation. Next, the transfer function of the master Omni is modified by using a joint inertia parameter of 0.0032 kg/m2 and a friction parameter of 0.0089 kg/m2 as specified the Quanser manual [19][20][21]. The slave Omni transfer function is replaced with the PHANTOM Omni device, for real time implementation of the system. It achieves the desired performance of stability and force reflection. A constant time delay of 0.1s is considered and the impedance controllers are tuned with coefficients Km = Ks = 10kg/s^2 and Bm = Bs = B = 6kg/s^2. These coefficients are varied to observe performance changes with different values.

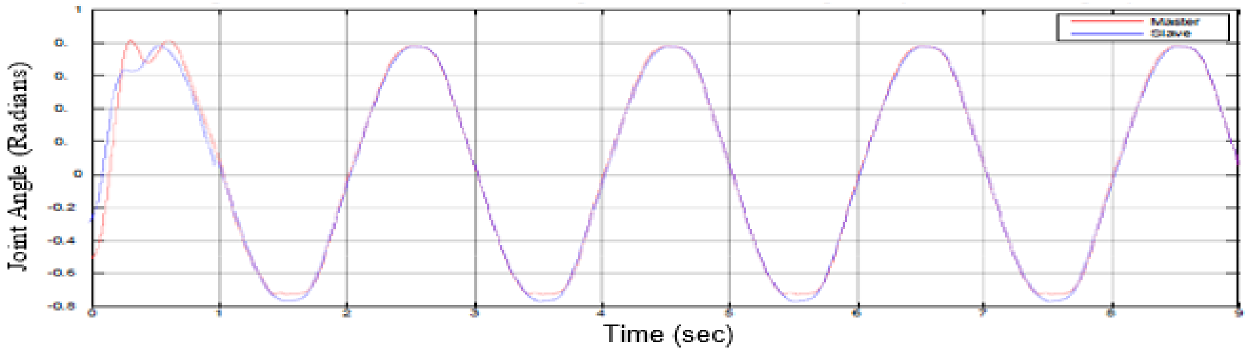

Figure 11: PD controlled Joint Angle for Unilateral Teleoperation in Free Space in Simulation

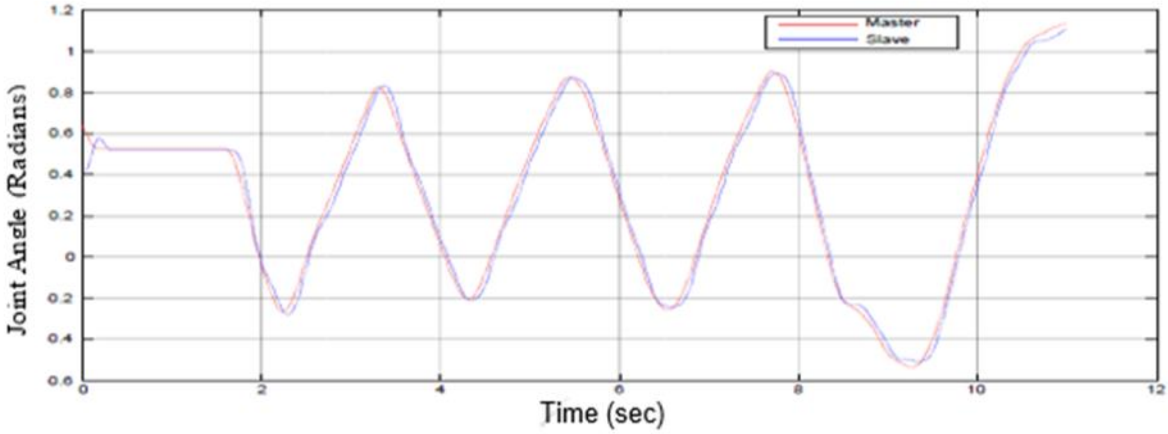

Figure 12: PD controlled Joint Angle for Unilateral Teleoperation in Free Space In Real Time

3.0 Result and Discussion

This work required a preliminary understanding of how the PHANTOM Omni works. PD and PI controllers were implemented for joint angle control in simulation and real time implementation on unilateral and bilateral teleoperation relations. This enabled smooth progression to the passivty based focus of matched **impedance control.** In simulation, a simple first-order transfer function is assumed to represent the model of the PHANTOM Omni joint considered by approximating many physical effects and dynamics. The implementation of this work was carried in different segments and the following results were obtained for;

3.1 Unilateral Teleoperation

Response for Unilateral Teleoperation in Free Space (Simulated Input) and (Real Time Input) are shown in figure 11 and figure 12. The PD controller guarantees stability and set point tracking in simulation and in real time implementation as shown in figures 11 and 12 respectively. This shows that it is suitable for controlling unilateral teleoperation systems.

3.1.1 Results for Unilateral Teleoperation with Time Delay

The controller was tested on the unilateral teleoperation system by introducing time delay in the communication between the master and the slave. To ascertain its ability to retain overall system stability, a range of time delays are explored and the response specifications analysed. Figure 13 to 15 show the performance of the

PD controlled bilateral teleoperation system in the presence of time delay. With a time delay of 0.01s, 0.1s and 1s, the stability and set point tracking of the system is retained as the time delay increases. This is because as the there is no feedback interconnection between the master and slave device. Hence, information transferred does not deteriorate due to the presence of the time delay.

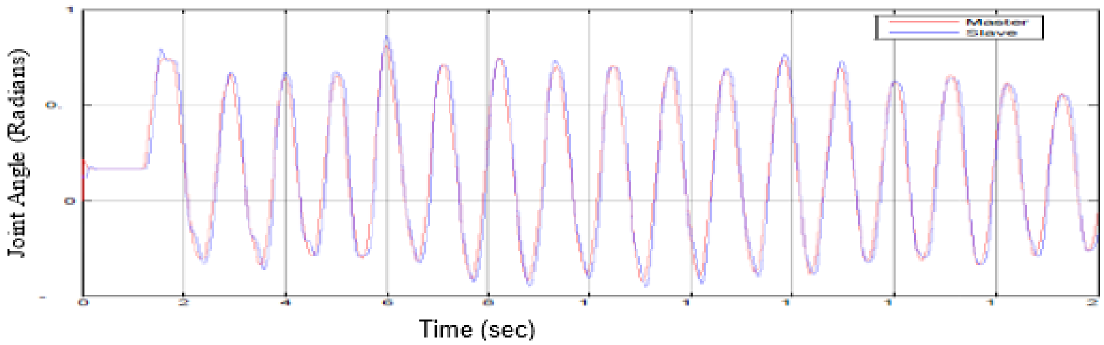

Figure 13: PD controlled Joint Angle for Unilateral Teleoperation with Time Delay of 0.01s

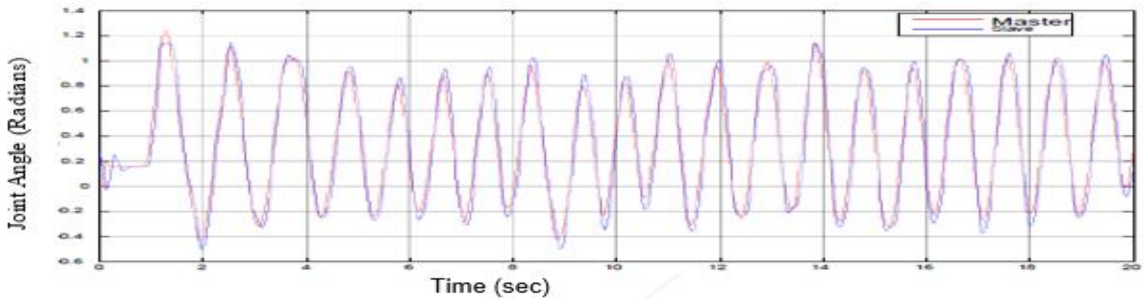

Figure 14: PD controlled Joint Angle for Unilateral Teleoperation with Time Delay of

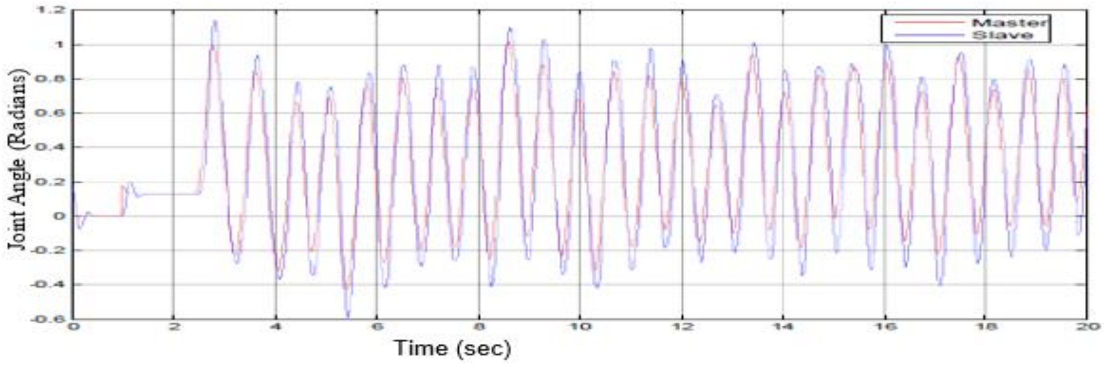

Figure 15: PD controlled Joint Angle for Unilateral Teleoperation with Time Delay of 1s.

3.2 Bilateral Teleoperation;

Response for Bilateral Teleoperation In Free Space, With Obstacle and with time delay are shown in figure 16, figure 17 and figure 18(a) and 18(b) respectively.

As shown in Figure 16, the PI controller guarantees stability and set point tracking in the real time implementation. Figure 17 also shows an ability to detect the force interactions of the slave with an obstacle in its environment. When an obstacle is introduced at 0.5 radians, an initial peak percentage overshoot of about 50% is compensated over time and set point tracking is achieved despite the obstacle interaction.

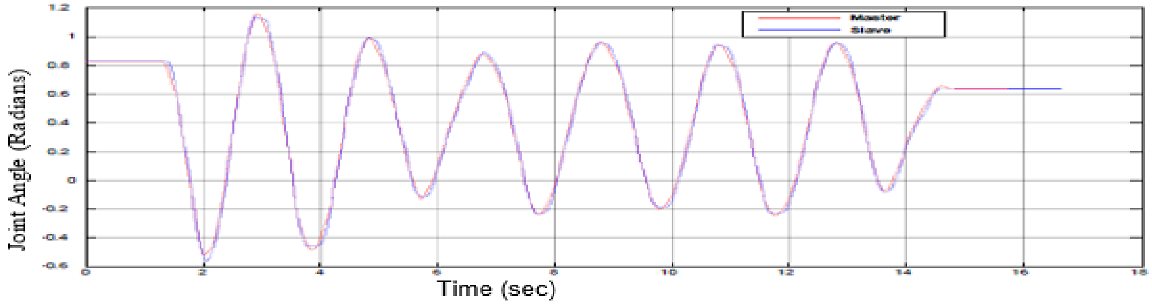

Figure 16: PI controlled Joint Angle for Bilateral Teleoperation in Free Space

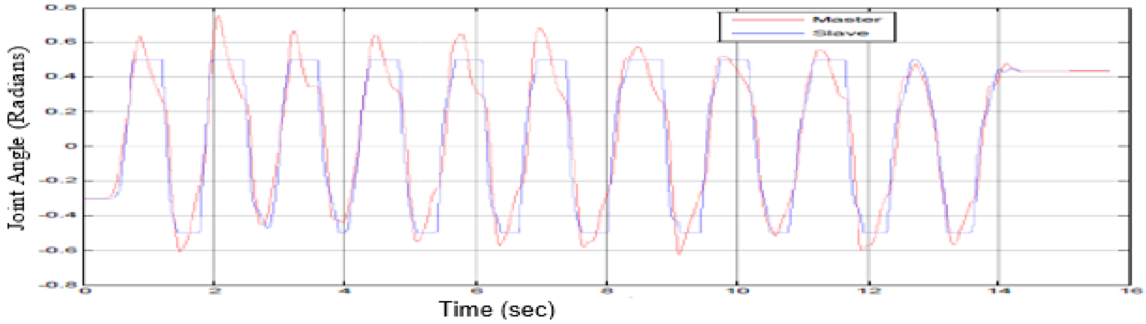

Figure 17: PI controlled Joint Angle for Bilateral Teleoperation with Obstacle

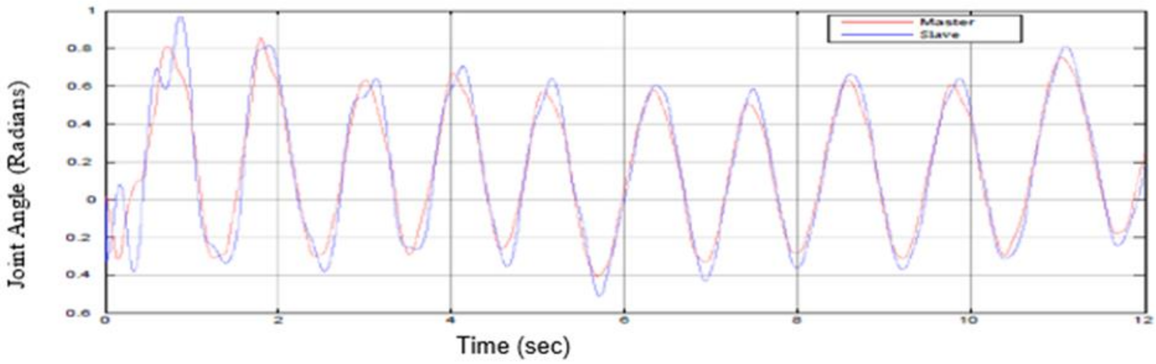

Figure 18 (a): Joint Angle for Bilateral Teleoperation with Time Delay of 0.01s

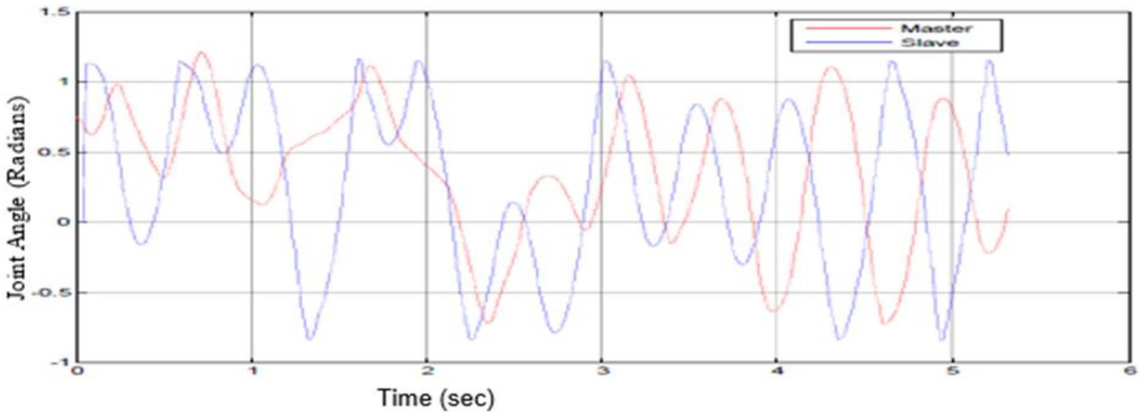

Figure 18 (b): Joint Angle for Bilateral Teleoperation with Time Delay of 0.05s

This affirms the enhancement of teleoperation systems by force reflection from the slave to the master as well as the suitability of PI controllers for set point tracking by speed control in bilateral teleoperation. This indicates that the use of PI controllers for bilateral teleoperation is effective for very small time delays but results in instability of the entire system when the time delay is increased to a certain range (above 0.05s in this instant).

3.3 Matched Impedance Bilateral Teleoperation with Time Delay and Slave-Environment Interaction

A range of values are examined and the resulting responses analysed in contrast with the desired performance of the matching Impedance controller.

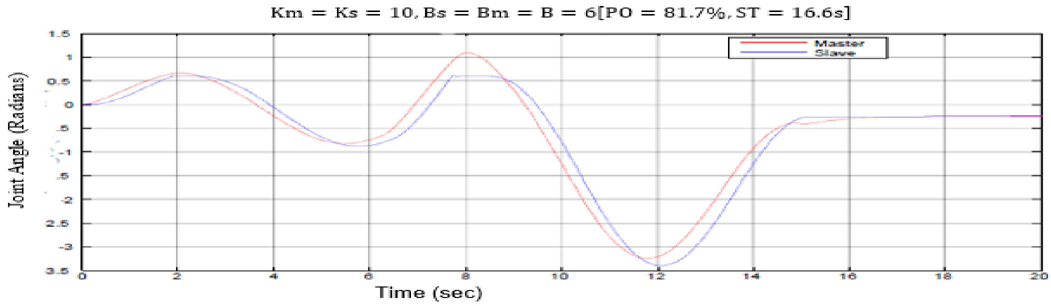

Figure 19: Joint Angle for Matched Impedance Bilateral Teleoperation (Km=Ks)

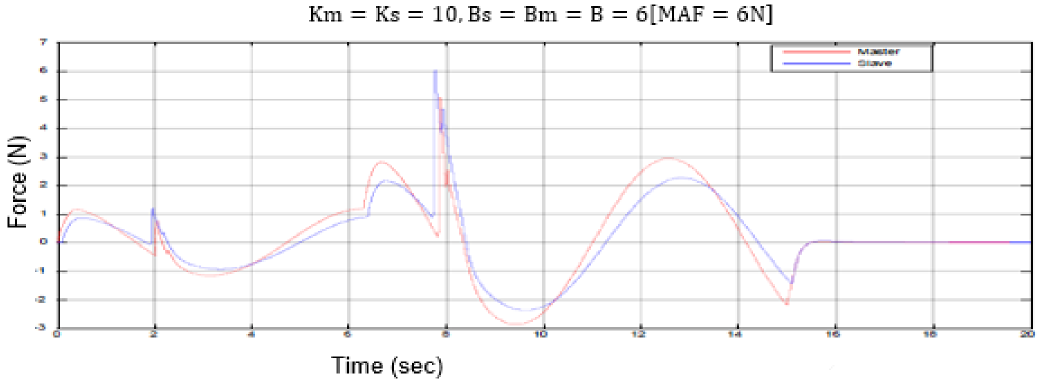

Figure 20: Force for Matched Impedance Bilateral Teleoperation (Km=Ks)

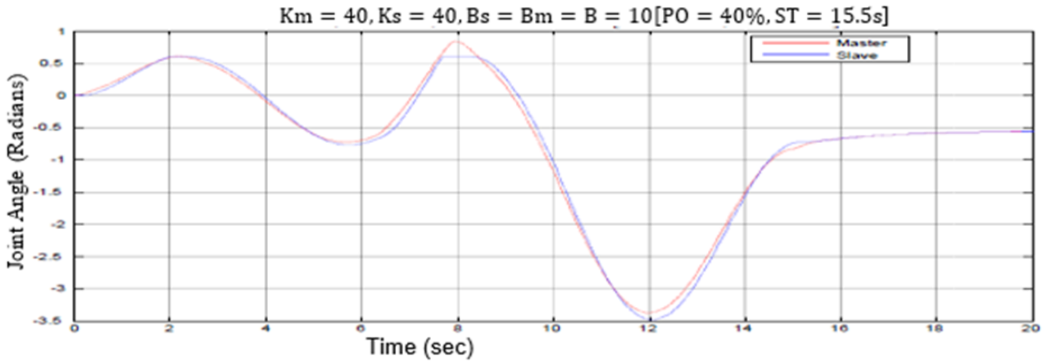

Figure 21: Joint Angle for Matched Impedance Bilateral Teleoperation (Km and Ks

3.3.1 Result of Varying the Controller Gains

By varying the master and slave impedance controller parameters, several combinations of controller gains and scattering operator values resulted in differing responses. The response specifications such as percentage overshoot (PO), settling time (ST) and maximum actuation force (MAF) is evaluated in each instant. As can be seen from Figures 19 to 21, increasing the value of Km reduces the settling time of the master-slave position response as well as the percentage overshoot of the slave joint angle by11.8%. Similarly, an increase in the value of Ks achieves the same effect on the percentage overshoot of the slave joint angle and a reduction in the settling time.

An actuation force of about 6 N is maintained when the slave device encounters an obstacle in the remote environment. This is due to the slave device's resistance to a change in direction imposed by the master device prior to the slave- obstacle interaction.

3.3.2 Result of Varying the Scattering Operator

In varying the scattering operator, differing responses are observed. The response specifications such as percentage overshoot (PO), settling time (ST) and maximum actuation force (MAF) is evaluated in each instant. From Figure 22 to Figure 25, it is seen that an increase in the value of the scattering operator results in a reduction in the percentage overshoot of the slave device's joint angle.

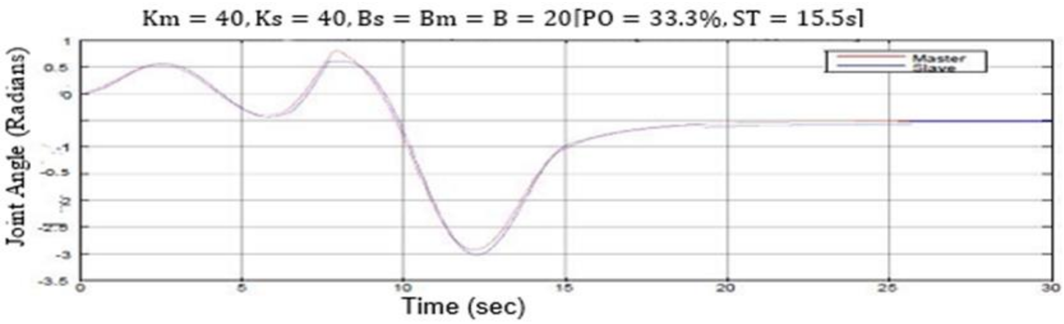

Figure 22: Joint Angle for Matched Impedance Bilateral Teleoperation (B Scaled)

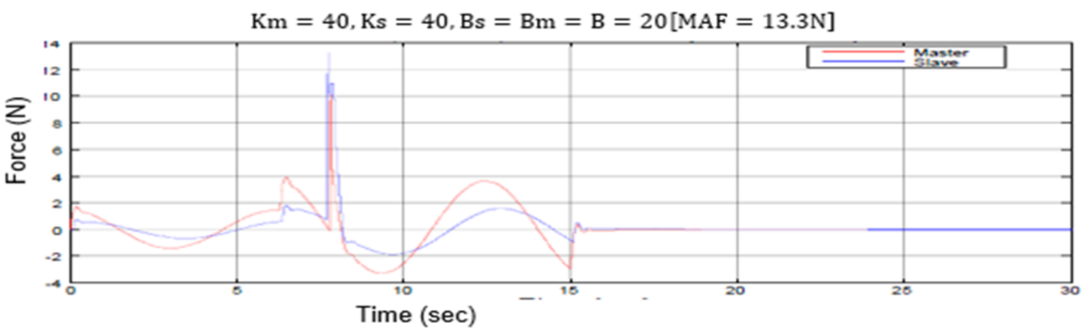

Figure 23: Force for Matched Impedance Bilateral Teleoperation (B Scaled)

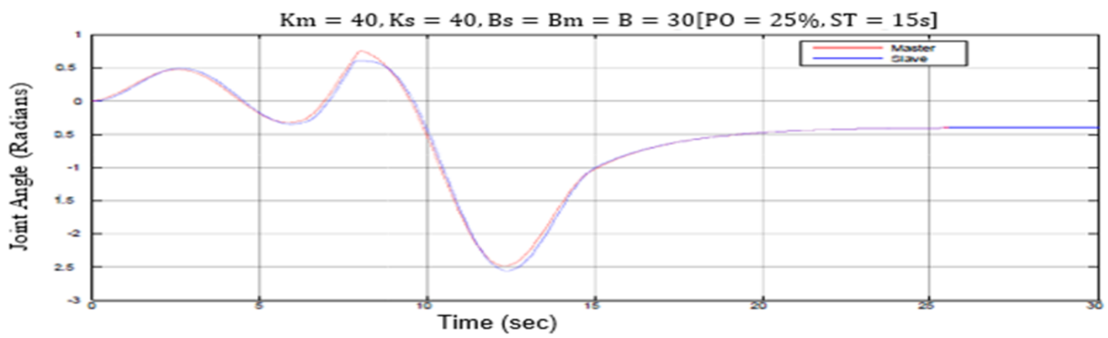

Figure 24: Joint Angle for Matched Impedance Bilateral Teleoperation (B Scaled)

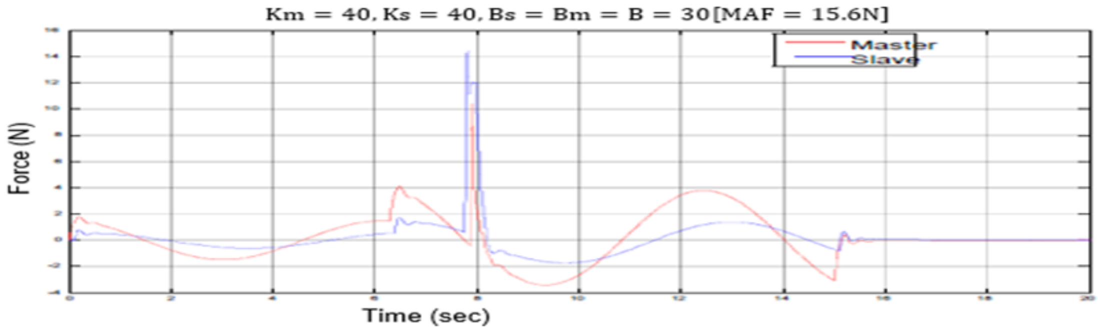

Figure 25: Force Response for Matched Impedance Bilateral Teleoperation (B Scaled)

A reduced settling time of 15 seconds is achieved at the expense of considerable increase actuation force. The maximum actuation force is recorded when the slave encounters an obstacle in its environment. An increase in actuation force is also observed when the master device initiates a change in the input signal. This is because the alteration of input signal is interpreted by the slave device as an obstacle preventing tracking of the pre-specified input signal trajectory.

4.0 Conclusion

The matched impedance controller developed using the wave variable formation achieves stable bilateral teleoperation for time delays up to 2 seconds. Considerable minimization of the position drift between master and slave devices is achieved by sufficiently tuning the controller parameters and the scattering operator. The matched impedance controller designed guarantees stability and robustness to time delays and force reflections from the slave's remote environment.

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