Simulation of Enhanced Force Limiting Gripper for Bilateral Teleoperation

R. M. M. Ruwanthika, A. M. Harsha S. Abeykoon
Department of Electrical Engineering
University of Moratuwa
Katubedda 10400, Moratuwa, Sri Lanka
ruwanthimaheshi@elect.mrt.ac.lk, harsha@elect.mrt.ac.lk

***Abstract*—This paper proposes an enhanced force limiting gripper to avoid object deformation when it is in contact with the slave due to excessive forces imposed by the master operator in bilateral control. The force lock protects the gripped object on the slave and the attainment of the force limit is notified to the master operator via a small vibration. Master operator is expected to experience a spring effect if the operator presses his leaver towards the force increasing direction. The continuous copying of the slave position as the reference to the virtual spring controller's spring equilibrium point allows smooth releasing. In addition to vibration the loss of reaction force coming from the slave environment could also be sensed by the master operator. Reversing of the applied force on master handle releases the object attached to the slave. In this proposed system sensor-less sensing is used. Disturbance Observer is used to estimate disturbances and Reaction Force Observer estimates reaction forces. The proposed gripper is having a jaw opening of 0.15 m which has linear 1-DOF. Simulation is conducted using real world linear motor parameters and simulation results prove the applicability of proposed system.**

Keywords—teleoperation; bilateral control; master slave; force control; gripper; virtual spring control; force lock

I. INTRODUCTION

Applications of robotics were restricted to production lines during past few decades. With the advancement of technology, robotic applications were introduced to agriculture [1], surgery [2], health care [3], care taking [4], assistance [5] and entertainment [6], etc. With the time, the distance between the operator and the working environment increased. The term "teleopertation" means operating a machine at a distance. Teleoperation is used to combat the distance, to improve accessibility in hazardous environments [2]. Technical advancements in teleoperation are useful in ultimate environments, such as disaster site, outer space, mines, atomic furnaces and etc. [7].

When operator is away from the actual environment accurate remote sensing is important in some of the applications. The feedback from the working environment can be a visual feedback or feedback from a sensor kept in the work site. Since working environment is away from the operator and feedback from the working environment to the operator is essential for accurate material handling, bilateral teleoperation is used [8].

The main idea of the bilateral control is sensing an environment remotely while controlling the remote manipulator based on the operator's intension. The word "bilateral" means controlling bilaterally. The operator who is giving commands is named as the master and the follower which is placed on the remote environment is named as the slave. The slave side is controlled through position and force information from the master side, and the master side is controlled by position and force information from the slave side [9].

A considerable attention should be given to grippers those are used in material handling. Selection of grippers depends on the task that it is used, environment, robot arm configurations, and control conditions [10]. Complex gripper design requires complex control mechanism and simple gripper design may cause poor grasping of the working object. Tactile sensing transduction based on piezoelectric and strain gauges are commonly used [11]. Tactile sensors based on piezoelectric materials could be used at the expense of a limited force range in sensing application and piezoelectric grippers provide limited displacement [12]. Although flexible gripper based on inflatable rubber pockets driven by a pneumatic actuator could grasp up to 20 kg, have the disadvantages of being large, heavy and need of an air compressor [13]. The proposed system is based on linear motor actuators and sensor-less force sensing is used.

The proposed system presented in this paper is modeled using two equal linear motors, hence no scaling is used and bilateral control is used for remote sensing. The design includes the single degree of freedom (DOF) gripper with a moving arm. Although there are many researches on bilateral control, few researches on grippers with bilateral teleoperation could be found. They have used kinesthetic and tactile sensors on the slave gripper for grip force feedback to master [14]. But in this proposed system, sensor-less sensing of forces via Disturbance Observer (DOB) and reaction Force Observer (RFOB) is used [8]. The observer based control strategy provides wider bandwidth when compared to the other systems. Although the concept of virtual spring controller is used in between the master and the slave [15] here it is used on master side to facilitate comfortable operation to master. The proposed system introduces a new concept of force lock based on the gripped object parameters which could be set by the operator.

Each object has a pre-defined force limit which could be exerted on it externally without deforming the object. In this proposed system a force lock is introduced on the slave side to protect the object from the excessive force applied through the master. Also a force limit feedback is sent to the master through a vibration notification when the reaction force on the slave is equal to the predefined tolerable force of the object. Proposed system includes a virtual spring controller on master side while force lock is engaged on the slave side. Unlocking mechanism is activated when reversing the force on the master. Master and slave follow bilateral control when it is not running in force lock mode.

II. MODELLING

Initially the system should follow the bilateral controller. When the slave manipulator is contacted with the object on the working environment, if master operator increases his holding force, a better grip of the object is achieved. The slave should obey the rules of bilateral control and should follow the master until it reaches the pre-defined force limit of the object. At the point of force limit of the object, the force controller is activated and the slave is locked at that force. When the force

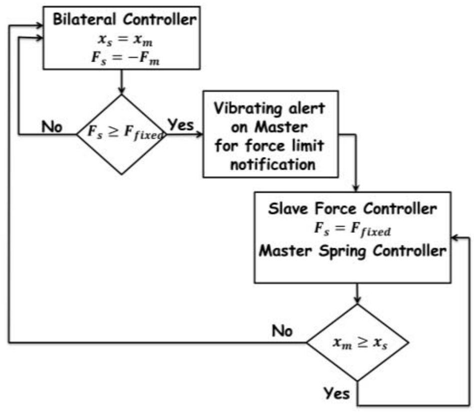

Fig. 1. Supervisory control block diagram of bilaterally operated enhanced force limiting gripper .

controller is activated, bilateral controller is disengaged and a vibration notification for a predefined period is given to the master operator to inform that the slave environment force limit has achieved. Further the master operator could feel loss of slave environment coming from the feedback. If master operator further increases the force on master manipulator, a virtual spring controller is activated where its equilibrium point is copied from the slave's position. However still the slave will be locked at the given force limit. This is important if the gripped object is further deformed under the fixed force. The virtual spring controller attempts to equalize the master slave positions in absence of the master force. The proposed bilateral controller is exemplified for a single DOF at the slave side. However if multiple DOF manipulators are used in bilateral teleoperation, locked object could be placed safely to the required position with minimal hazel where the operator need not to worry about the force limits of the object.

If master operator reduces his force on master manipulator and applied a reverse force on it and at the point of master position which is less than the slave position, force lock on the slave is disengaged and bilateral controller is engaged to release the object which is attached to the slave. Fig.1 shows the supervisory control block diagram of the propose system. The proposed system is modeled and simulated using MATLAB Simulink environment and in this section each model is elaborated. The symbols used in modeling are shown in TABLE 1.

TABLE I. TABLE OF VARIABLES

Symbol	Description
x_s	Slave position response
x_m	Master position response
F_s	Slave force response
F_m	Master force response
F_{fixed}	Object force limit
F^m_{ref}	Master force reference
F^s_{ref}	Slave force reference
F_{dis}	Disturbance force
$\hat{f}_{dis}$	Estimated disturbance force
g	Filter constant /DOB cut off frequency
K_{fn}	Nominal motor force constant
M_n	Nominal motor mass
F_{cmd}	Force command
$F_{reaction}$	Reaction force
I^a_{ref}	Reference armature current
M	Mass of object
k	Spring constant
B	Viscous friction coefficient
x	Linear position response
x^s_{eq}	Slave equilibrium position
s	Laplace operator
$\hat{f}_{human}$	Estimated master force
$\hat{f}_{env}$	Estimated slave reaction force

A. Bilateral Controller

Fig. 2 shows the basics of bilateral control. For bilateral control without scaling, master and slave should follow same positions as well as law of action and reaction between the operator and the slave environment should also be followed.

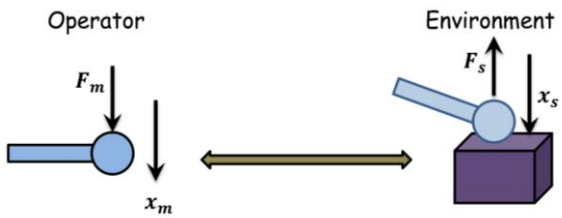

Fig. 2. Basics of bilateral control following same positions and equal but opposite action and reaction forces by master and slave.

Equation (1) and (2) are the basic equations of bilateral control.

$$x_m - x_s = 0 \quad (1)$$

$$F_m + F_s = 0 \quad (2)$$

The equations (1) and (2) are transformed to (3) and (4) as accelerations considering equal masses in master and slave manipulators.

$$\ddot{x}_m - \ddot{x}_s = 0 \quad (3)$$

$$\ddot{x}_m + \ddot{x}_s = 0 \quad (4)$$

Equation (3) represents the position relationship which is known as differential mode and (4) represents relationship of force which is called the common mode between the master and the slave. This can be attributed to the sign of the equations. For the optimal goal of bilateral control (3) and (4) are transformed as follows.

$$\ddot{x}_m - \ddot{x}_s = \ddot{x}_{com} \rightarrow 0 \quad (5)$$

$$\ddot{x}_m + \ddot{x}_s = \ddot{x}_{diff} \rightarrow 0 \quad (6)$$

Fig. 3 shows the block diagram of bilateral controller which satisfies (5) and (6). Master is fed with the position response of slave as the reference and master position response as the feedback. Slave is fed with the position response of master as the reference and slave position response as the feedback. These two position controllers in each manipulator consist of Proportional Derivative (PD) controller.

Disturbance Observer is used to estimate the disturbance force on the master and the slave and corresponding current required for compensating the disturbance is fed back to the master and the slave. Reaction Force Observer is used to estimate the reaction forces acting from the master and the slave environment and force error is fed to both master and slave control blocks to align the force response of both master and slave.

B. Disturbance Observer and Reaction Force Observer

Dynamic equation of a linear motor can be represented as (7) and generated force from the motor can be represented as (8).

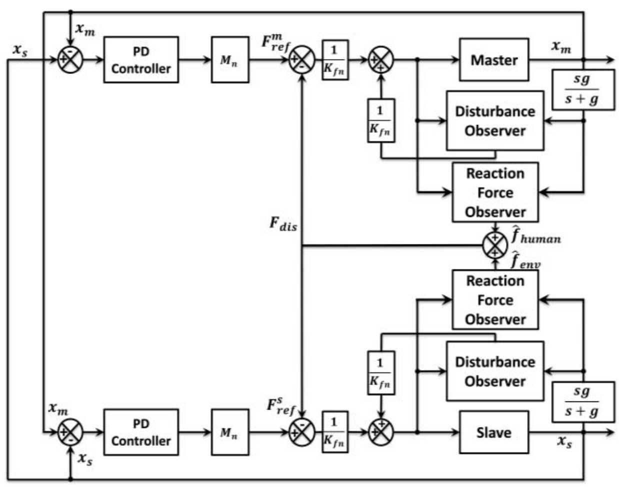

Fig. 3. Block diagram of bilateral controller.

$$M\ddot{x} = F_g - F_l \quad (7)$$

$$F_g = K_f I^a_{ref} \quad (8)$$

M, F_g, F_l and K_f mean motor mass, generated force, load force and motor force constant. Load force can be represented as (9).

$$F_l = F_{int} + F_{ext} + (F + B\dot{x}) \quad (9)$$

F_{int}, F_{ext}, F and $B\dot{x}$ mean interactive torque, reaction force of the mechanical load, static friction and viscous friction. Equation (7) can be re-written by substituting from (8) and (9).

$$M\ddot{x} = K_f I^a_{ref} - F_{int} + F_{ext} + (F + B\dot{x}) \quad (10)$$

Parameters M, K_f are subjected to variations and estimation errors. Therefore these can be re-written in terms of nominal values and variations.

$$M = M_n + \Delta M \quad (11)$$

$$K_f = K_{fn} + \Delta K_f \quad (12)$$

By substituting (11) and (12) to (10) and rearranging, (13) can be derived.

$$M_n\ddot{x} = K_{fn} I^a_{ref} - (F_{int} + F_{ext} + F + B\dot{x} + \Delta M\ddot{x} - \Delta K_f I^a_{ref}) \quad (13)$$

The term within the parenthesis in (13) is called as total disturbance to the system F_{dis}.

$$F_{dis} = F_l + \Delta M\ddot{x} - \Delta K_f I^a_{ref} = F_{int} + F_{ext} + (F + B\dot{x}) + (M - M_n)\ddot{x} + \left(K_{fn} - K_f\right) I^a_{ref} \quad (14)$$

By rearranging,

$$M_n\ddot{x} = K_{fn} I^a_{ref} - F_{dis} \quad (15)$$

Thus, F_{dis} can be calculated as follows.

$$F_{dis} = K_{fn} I^a_{ref} - M_n\ddot{x} \quad (16)$$

Fig. 4 shows the block diagram of the disturbance observer. Disturbance is calculated using I^a_{ref} and $\dot{x}$. Estimated disturbance $\hat{f}_{dis}$ in (17) is derived from the disturbance, passing through the low pass filter. Cutoff frequency of the low pass filter is denoted by g.

$$\hat{f}_{dis} = \frac{g}{s+g} F_{dis} \quad (17)$$

This disturbance observer is used to estimate the reaction force without using a force sensor by subtracting the internal disturbance of the system. Fig. 5 shows the block diagram of the reaction force observer.

C. Force Controller

The force limit of the slave environment should be specified by the user. The force response of the object can be modeled as shown in (18).

$$F = M\ddot{x} + B\dot{x} + kx \quad (18)$$

F is the force response of the object and other symbols are defined in the TABLE 1.

When the slave manipulator is in contact with the object, if the master is increased his force to tighten the object between the slave gripper arms, the slave obeys the rules of bilateral control and follows the master until it reaches the specified force limit of the object. When the reaction from the slave is equal or it exceeds the force limit, force controller is activated and slave manipulator is locked at that maximum force limit.

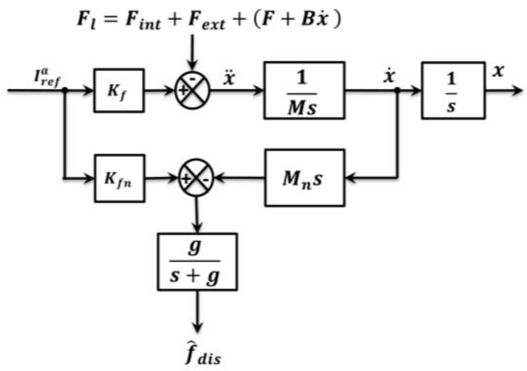

Fig. 4. Block diagram of disturbance observer which estimates total disturbance to the system.

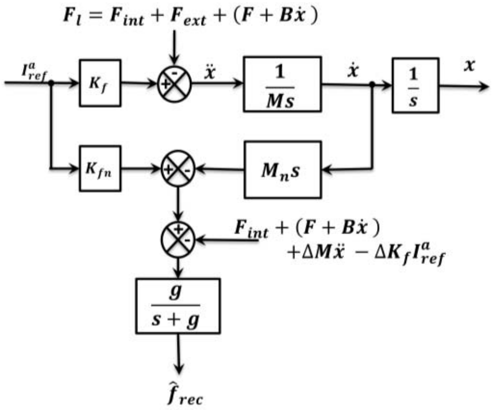

Fig. 5. Block diagram of reaction force observer which estimates reation force without force sensors.

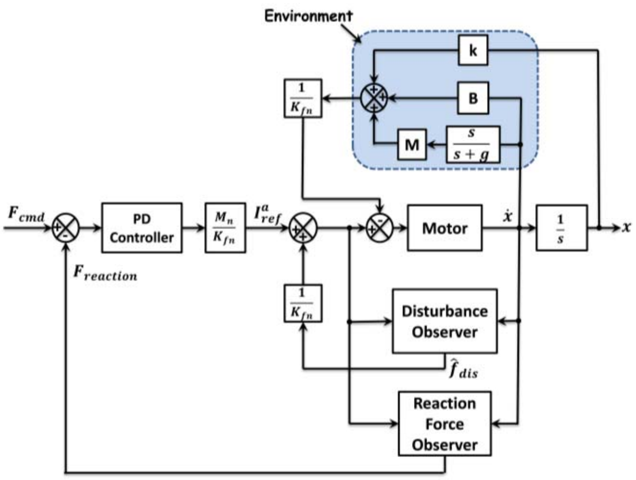

Fig. 6. Block diagram of force controller which activates when the reaction from the slave is equal or it exceeds the predefined force limit.

Fig. 6 shows the block diagram of the force controller. In this, user specified force is taken as the reference force and the reaction force from the RFOB of the slave is taken as the feedback force. Force error is fed to the PD controller. The output of the PD controller is converted to the corresponding current reference to the slave motor. The slave disturbance is estimated via DOB and corresponding compensating force is fed to the slave motor current input.

D. Vibrating Alert

Fig. 7 shows the block diagram of the vibrator. A high frequency sinusoidal signal is added on to the slave equilibrium position which corresponds to the position at the time of force controller is engaged to the slave. It is used as the reference to the master position controller in bilateral controller. This function is available only for 500ms and it indicates that the force limit on the slave environment has reached.

E. Spring Controller

When the force controller is engaged onto the slave system, a virtual spring controller is attached onto the master manipulator. Fig. 8 shows the block diagram of the spring controller. The spring effect is produced around the equilibrium position which corresponds to the slave's position. If the master's intension is to press the slave object by increasing the master position response, spring effect is felt by the master. Thus when the object is gripped and locked at the maximum allowable force, master spring controller would not be having any effect on the slave object. Spring controller's intension is to notify the user and also equalize the positions in this locked mode.

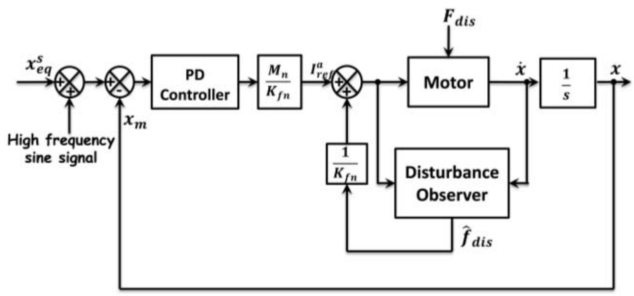

Fig. 7. Block diagram of vibrator which facilitates vibration notification on the master when slave force limit is reached.

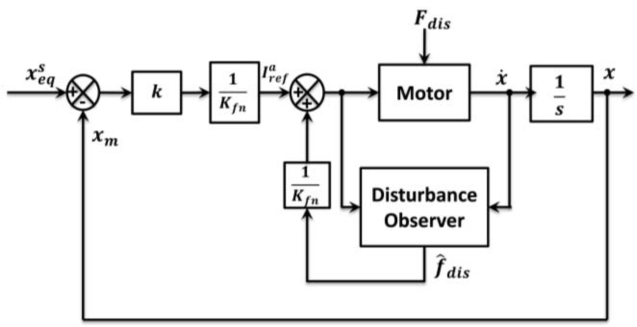

Fig. 8. Block diagram of spring controller which notifys the user and equalizes the positions in locked mode.

III. Results

A. Test conditions

The simulation is carried out using two equal linear motors and TABLE II shows the relevant parameters of the simulation. It is assumed that the spring constant of the object is varying with the object pressing and x denotes the displacement. It is assumed that at the point of starting of simulation both master and slave grippers are fully opened and those spans are set to be 0.15m.

Fig. 9 shows the applied force profile by the master. Within the first 5s master applies the force to overcome the friction of the system and during this period both master and slave move 0.05m obeying the rules of the bilateral control. A modeled object which is having 0.1m diameter is placed in between the slave gripper arms. Therefore slave is in contact with the object when it is moved 0.05m. Now master increases his force gradually to reach 10N at 10s. The assumed force limit of the object is 9N.

By observing Fig. 10 which shows the slave force response, it can be observed slave force have reached 9N around 9.5s. Now force controller is activated and therefore slave force response remains at 9N, although the master changes his force profile without reversing the force. When master reverses his force and master position response is less than or equal 99% of the slave position response, the object is released and bilateral control is switched back. Fig. 11 shows the master position response and Fig. 12 shows the slave position response. It can be observed that until the object is in contact, the system is accelerating from 0s to 5s. After slave is in contact with the object, due to force applied on master, object is compressed until it reaches its force limit. With the activation of the force controller, the slave position response remains unchanged due to the object property until master applies the releasing force.

TABLE II. Parameter Table

Parameter		Value
K_{fn}	Force constant	24N/A
M_n	Motor shaft weight	0.40kg
$K_{P,m}$	Proportional gain of master	800
$K_{d,m}$	Derivative gain of master	60
$K_{P,s}$	Proportional gain of slave	300
$K_{d,s}$	Derivative gain of slave	60
K_P	Proportional gain of force controller	3.3
K_d	Derivative gain of force controller	1.1
g	Filter constant of DOB	350
B	Viscous friction coefficient	5N/ms^{-1}
M	Mass of object	0.1kg
k	Spring constant of object	250N/m^{-1}
K_{sp}	Spring constant of spring controller	100N/m^{-1}
T_s	Sampling period	100µs

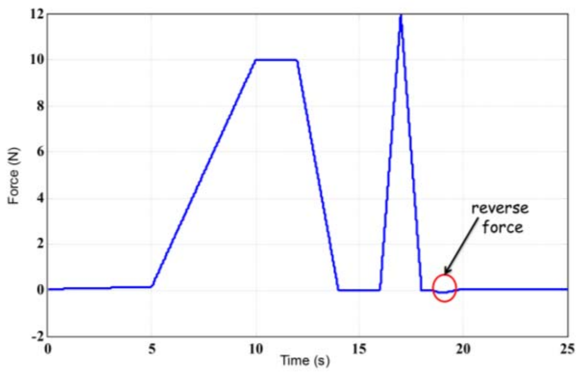

Fig. 9. Master force profile.

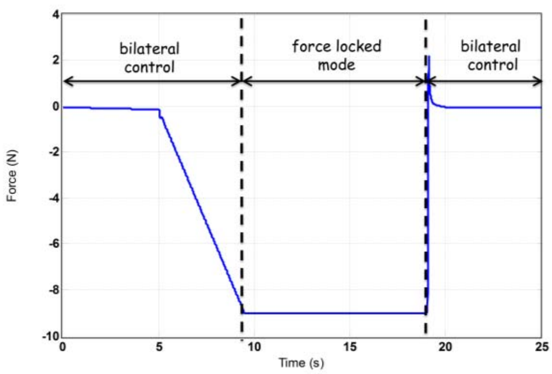

Fig. 10. Slave force response.

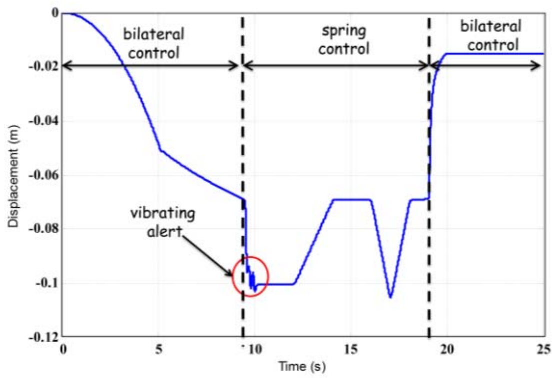

Fig. 11. Master position response.

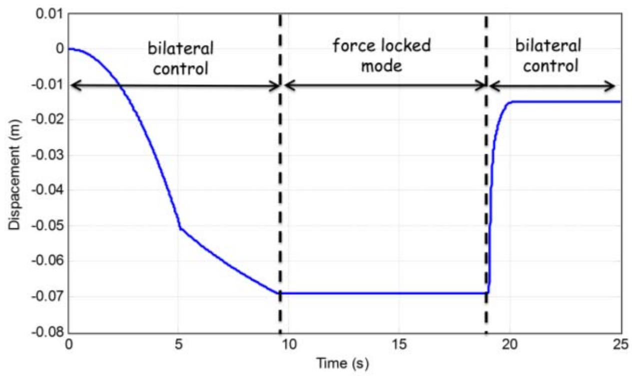

Fig. 12. Slave position response.

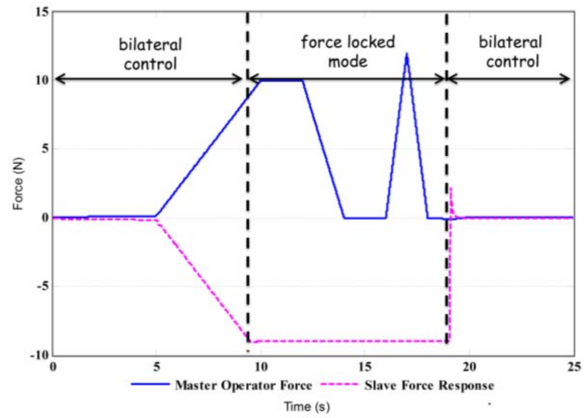

Fig. 13. Master force profile and slave force response on it.

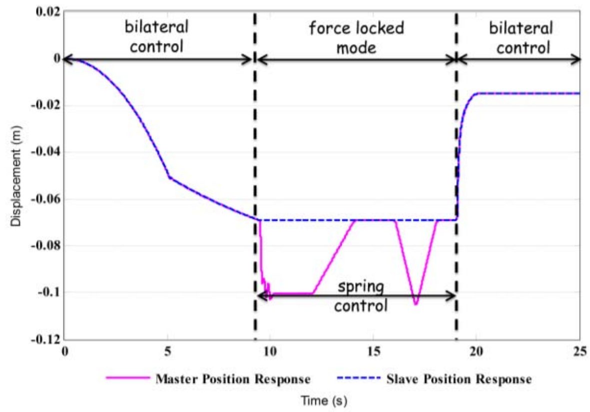

Fig. 14. Master and slave position response.

The spring controller which is attached to the master during force locked period on the slave is controlling the master position. The vibrating alert on master is also shown.

Fig. 13 shows master applied force and slave force response in same figure where operating regions are marked. Fig. 14 shows master and slave position responses in same figure where regions are marked. Master and slave follow bilateral control when it is not running in force lock mode. When the object is released both master and slave follows bilateral control and settle down according to the applied force on the master.

IV. Conclusion

In this paper an enhanced gripping mechanism to be used with the bilateral teleoperation was proposed. The proposed bilateral controller is exemplified for a single DOF at the slave side. However, if multiple DOF manipulators are used in bilateral teleoperation, locked object could be placed safely to the required position with minimal hazel where the operator need not to worry about the force limit of the object. The force lock protects the gripped object on the slave and the attainment of the force limit is notified to the master operator via a small vibration. In addition to the vibration the loss of reaction force coming from the slave environment could also be sensed by the master operator. The force limit of the object is set by the operator based on the experience and the object properties. Virtual spring controller attempts to equalize the master slave positions in the locked mode. The proposed system is modeled and simulated using MATLAB Simulink environment using real world parameters. Thus a similar response could be expected from the practical results as well.

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