Bilateral Control with Compliant Force Lock for Safety Enhancement

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***Abstract*—This paper proposes a force feedback compliance force lock for biltateral control based on sensor-less sensor Reaction Force Observer (RFOB). The force limit is defined by the operator in advance based on the experience. The force lock protects the object which is in contact with the slave actuator from excessive force imposed by the master operator in bilateral control. A small vibration has been introduced to notify the attainment of the force limit to the master operator. Furthermore, if master operator wishes to increase his applied force, he will experience spring effect. The equilibrium point of virtual spring controller which is continuously copied from the slave force locked position aligns master and slave positions at force lock mode. The loss of reaction force occurs at the transition from bilateral control to force lock and vice versa has been removed to regain system stability and to facilitate comfortable operation for the operator. Releasing logic of force lock can be determined by the operator. The proposed system is validated with experiments and results prove the concept of RFOB based force feedback compliance force lock for bilateral control.**

Keywords*—*Bilateral control, master-slave, disturbance observer, reaction force estimator, virtual spring control, force lock

I. Introduction

With the advancement of technology, the restricted applications of robotics on production lines were spread to agriculture, care taking, surgery, assistance, health care and, entertainment, etc. Teach pendent or unilateral robots do not provide force feedback to the operator. As the distance between the operator and the robot increases the remote environment force feedback is essential for sensitive activities like care taking, surgery, and radioactive material handling for safety enhancement. The feedback from the remote environment could be a visual feedback or feedback from sensors kept in the remote environment. Visual feedbacks are incapable of justifying the force magnitudes of dynamic motions. There exists the risk of human error when assuming the force magnitude.

Real time remote force sensing and force adjustment can be achieved through acceleration based bilateral control [1]. Advanced bilateral teleoperation aims to achieve high haptic perception with the operator feeling of telepresence with perfect position tracking and force control simultaneously in real time.

Successful handling of object in a remote environment requires sensing remotely and firmly holding the object without damage. Remote object handling robots use grippers as the end effector. When handling delicate objects operator should ensure that the grasped object is not damaging by the excessive force applied through the end effector and should maintain static grip force sufficient to firmly hold the object as a lock. The risk of human error in assuming the applied force on remote object via end effector is possible to omit by introducing the bilateral control to the system. Da Vinci Surgical system, macro-micro cell manipulation, nuclear accident robots, hot cell robots are typical examples of sensitive activities which lack haptic feedback where operator relys on vision feedback.

The research on compliance force grippers have been conducted from decades [2] - [7]. The compliance force has been achieved through gripper mechanical design, gripper material and using various types of force sensors like pressure sensors, strain gauges, Force Sensing Resister (FSR), and piezoelectric sensors, etc [8]. These studies have been conducted for unilateral robot arms. Therefore there is no grip force feedback to the operator. Limited research on grasp force sensing during bilateral teleoperation could be found in the work of [9] and [10] in which grasping force have been detected through kinesthetic, tactile sensors and strain gauges. Force sensors occupy space and sometimes cannot be placed where the force needed to be measured. In studies [9] and [10] force-limiting feature which is going to be presented by this paper is not available when handling remote delicate objects.

Maintaining compliance force continuously on the slave is important to protect grasped object and to avoid slipping from gripper arms. This paper proposes the novel concept of force lock to be used with bilateral control. Authors use Reaction Force Observer (RFOB) as it is an extension to the Disturbance Observer (DOB) which does not occupy space [11], [12], [13]. Simulation of force feedback gripper for bilateral teleoperation could be found in [14]. This paper modifies the control algorithm in [14] to regain system stability. The introduced force lock in which force limit is set by the operator experience or series of compression tests allows operator freedom to release his hand during force lock mode. The proposed system undergoes several step transition stages. The system continuously developed to regain the system stability during transitions and to facilitate operator comfort. The proposed system is testes with 1 Degree of Freedom (DOF) master-slave actuators.

The paper is organized as follows. The modeling of force lock to be used with bilateral control is considered in section II. In section III, experimental results are presented in order to verify the proposed novel method. Finally, this paper is summarized and concluded in section IV.

II. Modeling

The force lock system protects the slave environmental object from the excessive force applied through the master in bilateral control. Primarily the system is following the acceleration based bilateral controller. When the slave manipulator is in contact with the object, master operator sense the reaction force exerted on the slave manipulator by the object in real time. The operator increases his holding force to achieve a better grip. Every object has a predefined tolerable force limit. Authors predefine the force limit.

When the force limit is attained, it will be notified to the master operator in terms of a vibration. Slave object is preserved as the proposed lock maintained the specified maximum force. After engaging the force lock, master operator is feeling as if he is pressing a spring. This feeling is generated using a virtual spring controller placed on the master side. The lock will be released when the operator intends to release the object. Fig. 1 shows the basic concept. Fig. 2 shows the control flow chart of force lock. The operator could modify the lock release condition. Master and slave follow bilateral control when it is not running in force lock mode. Thus, the main phases available in the force lock are bilateral control, vibration notification, force control at the slave side, virtual spring sensation at the master side and the object release.

A. Disturbance Observer and Reaction Force Observer

Disturbance observer(DOB) [11], [12] and reaction force observer (RFOB) [13] has been implemented for robust motion control. The DOB observes disturbance forces without force sensors. Estimated disturbance force can be represented as (1).

$$\hat{f}_{dis} = \frac{g_{dis}}{s + g_{dis}} \left(K_{fn} I^a_{ref} + M_n g_{dis} \dot{x}\right) - M_n g_{dis} \dot{x} \tag{1}$$

The notations $\hat{f}_{dis}$, g_{dis}, s, K_{fn}, I^a_{ref}, M_n, $\dot{x}$ respectively denote estimated disturbance force, cutoff frequency of the low pass filter, Laplace operator, nominal motor constant, motor current reference, nominal motor mass and velocity response. The feedback of the estimated disturbance force compensates the low frequency component of the disturbance which is below the cut off frequency g_{dis} of low pass filter.

The DOB is furthermore modified for reaction force estimation as RFOB [13]. This is achieved by identifying internal parameter variation and friction component in the system previously. In this research, frictional forces has not considered. The calculation of estimated external force $\hat{f}_{ext}$ is shown in (2).

$$\begin{aligned}\hat{f}_{ext} = \frac{g_{rec}}{s + g_{rec}} &\left(K_{fn} I^a_{ref} + M_n g_{rec} \dot{x} - (F_{int} + F_{fric}\right. \\ &\left. + \Delta M \ddot{x} + \Delta K I^a_{ref})\right) - M_n g_{rec} \dot{x}\end{aligned} \tag{2}$$

The notation g_{rec}, F_{int}, F_{fric}, ΔM, ΔK, $\ddot{x}$ respectively denote the cutoff frequency of the low pass filter, interactive force, frictional force, motor mass variation, motor constant variation, and acceleration. The RFOB estimates reaction force as quickly as possible by increasing the cutoff frequency in the stability range.

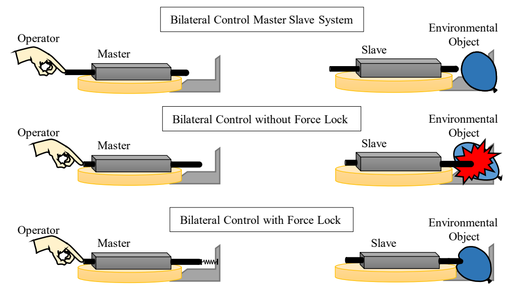


Fig. 1. Concept of bilateral control with force lock.

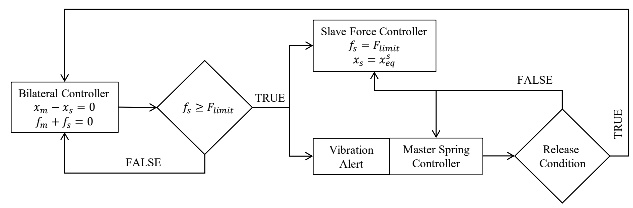


Fig. 2. Control flow chart of force lock.

B. Bilateral Controller

The bilateral control facilitates human operator to interact with remote environment through interface devices while sensing the haptic feedback remotely. Acceleration based 4 chanel bilateral controller has been implimented in vertual mode space [15]. A position controller in the differential mode space and a force controller in the common mode space. Equations (3) and (4) show the objective functions of bilateral control without scaling.

$$x_d = x_m - x_s = 0 \tag{3}$$

$$f_c = \hat{f}^{ext}_m + \hat{f}^{ext}_s = 0 \tag{4}$$

The notations x_d, f_c, x and subscript m, s respectively denote position in the differential mode space, force in the common mode space, position response, master and slave. As force and position are said to be orthogonal and could not be achieved simultaneously both (3) and (4) are transformed to a common dimension of acceleration as in (5). Because position control and force control are now in common dimension of acceleration objective functions of bilateral control can be achieved simultaneously through acceleration control architecture. $\ddot{x}$ denotes the acceleration.

$$\begin{bmatrix}\ddot{x}_c \\ \ddot{x}_d\end{bmatrix} = \begin{bmatrix}1 & 1 \\ 1 & -1\end{bmatrix}\begin{bmatrix}\ddot{x}_m \\ \ddot{x}_s\end{bmatrix} = \begin{bmatrix}0 \\ 0\end{bmatrix} \tag{5}$$

Reference values of the master and slave motors are controlled as (6) and (7). $C_p(s) = K_p + K_d s + \frac{K_i}{s}$ is a position controller gain and $C_f = K_f$ is a force controller gain.

$$\ddot{x}^{ref}_m = C_p(s)(x_s - x_m) - C_f(\hat{f}^{ext}_m + \hat{f}^{ext}_s) \tag{6}$$

$$\ddot{x}^{ref}_s = C_p(s)(x_m - x_s) - C_f(\hat{f}^{ext}_m + \hat{f}^{ext}_s) \tag{7}$$

Fig. 3 shows the block diagram of bilateral controller which satisfies (5). The bilateral controller uses DOB to estimate the disturbance forces [11], [12]. Thus, corresponding current required to compensate the disturbances is given as feedback to the master and the slave. Consequently, RFOB is used to estimate the reaction force acting on the master and the slave environment [13].

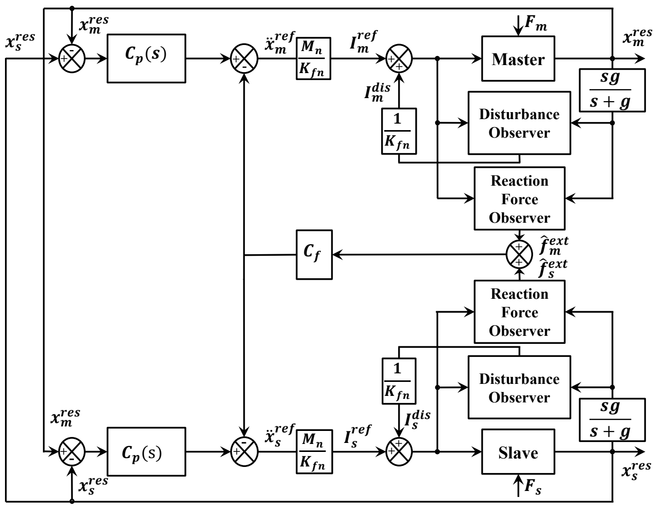


Fig. 3. Control block diagram of bilateral control.

C. Force Controller

The force controller acta as a lock and maintains the operator defined force limit F_{limit} continuously on the slave environmental object. The force limit is previously defined based on operator experience or conducting series of compresion tests. It is sufficent to firmly hold the object without damage. Explicit force control is implimented [16] in this study. The lock will be activated when the slave environmental reaction force is equal or exceeding the predefined force limit. The slave actuator follows force limit F_{limit} until master operator satisfies the object release conditions. During active force lock the master and the slave no longer follow the bilateral control. The reference current I_s^{ref} is generated as in (8). Fig. 4 shows the control block diagram of the force controller.

$$I_s^{ref} = (K_{p,F} + sK_{d,F} + \frac{K_{i,F}}{s})(F_{limit} - f_s^{ext})(\frac{M_n}{K_{fn}}) \quad (8)$$

The force limit F_{limit} is taken as the reference force. The estimated reaction force of the slave environment via the RFOB of slave actuator, $\hat{f}_s^{ext}$ is taken as the feedback. The force error is fed to the PID controller. The disturbances are also estimated via DOB and corresponding current I_s^{dis} required to compensate the disturbances is given as feedback to the slave.

D. Spring Controller

During active force lock on the slave side, the objective equations (3), (4) of bilateral control are violated. The slave actuator follows force controller as a local safety function to protect the object as in (8) and the common mode space equation (4) is replaced. As a results master operator feels the loss of reaction force coming from the slave environment. It feels as a step force reduction and causes a forward position step. This could be used as a force limit achievement notification as mentioned in [14]. In real world applications, it is undesirable and the spring controller used in [14] is modified as shown in Fig. 5 to facilitate the sense of continuous force increasing to the master operator. The force limit F_{limit} and RFOB force feedback f_m^{ext} is introduced.

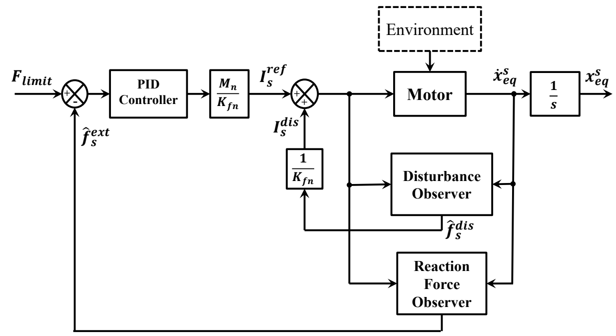


Fig. 4. Control block diagram of force controller.

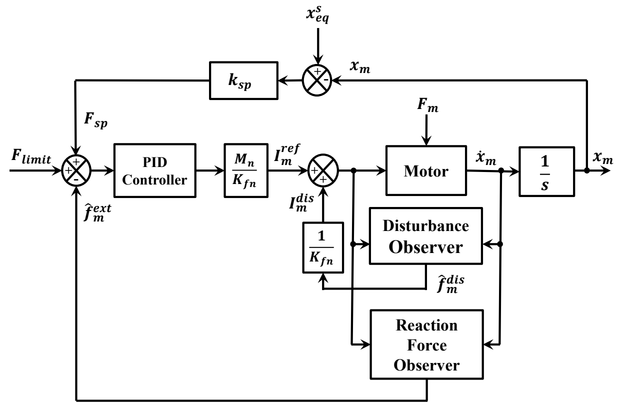


Fig. 5. Control block diagram of spring controller.

The spring force F_{sp} is produced as in (9) around the equilibrium position x_{eq}^s which is continuously copied from the slave position during active force lock. The notation k_{sp} denotes spring coefficient. The force reference F_{ref} of modified spring controller can be presented as (10).

$$F_{sp} = k_{sp}(x_{eq}^s - x_m) \quad (9)$$

$$F_{ref} = F_{limit} + k_{sp}(x_{eq}^s - x_m) \quad (10)$$

The force error is fed to the PID controller. The disturbances are estimated via DOB and required compensating current I_m^{dis} is given as feedback to the master. The virtual spring controller tries to equalizes the positions in the lock mode. If operator applies a force exceeding force limit F_{limit}, operator feels as he is pressing the spring. This would not be having any effect on the locked object on the slave.

E. Vibration Notification

A vibration signal is created on the master actuator to notify the force limit attainment of the slave environment. This is available for 500ms just after the force lock is activated on the slave side. A square wave signal is added on to the slave equilibrium position x_{eq}^s which is copied from the slave position during active force lock. It is used as the reference to the master position controller as in (11).

$$x_m^{ref} = x_{eq}^s + kb \quad (11)$$

Notations k, b denote vibration magnitude gain and digit 1 or 0 for squre wave state. Fig. 6 shows the control block

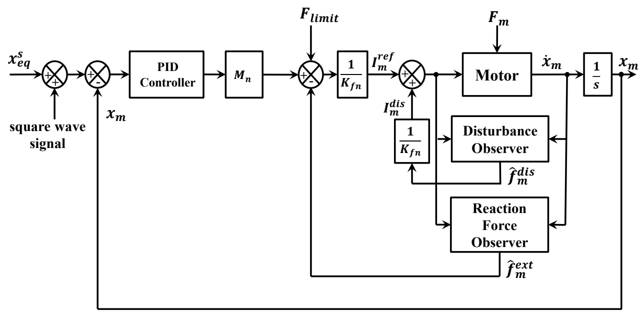


Fig. 6. Control block diagram of vibration controller.

TABLE I. OBJECT RELEASE.

Condition	Operator free hand
$x_{eq}^s - x_m < 0$	X
$\hat{t}_m^{ext} < T_{limit}$	X
$(x_{eq}^s - x_m < 0)\&(\hat{t}_m^{ext} < T_{limit})$	X
$\hat{t}_m^{ext} < 0$	$\surd$
$(x_{eq}^s - x_m < 0)\&(\hat{t}_m^{ext} < 0)$	$\surd$

diagram of the vibration controller. The controller in [14] is modified by introducing the force limit F_{limit} and RFOB force feedback f_m^{ext} to avoid untying the operator hand from master side step force reduction due to slave environment reaction force loss in bilateral control. This facilitates the sense of continuous force increasing to the master operator. The vibration signal does not effect on the locked object on the slave.

F. Object Release

Object release condition is possible to decide by master operator providing him operator flexibility. The release conditions considered in this study are listed in Table I. These conditions determine whether operator can release his hand with active force lock or has to hold the hand on the master actuator during complete process of bilateral motion and force lock. The output of force limit F_{limit} and RFOB force feedback f_m^{ext} of spring controller equilize to the common mode space equation (4) when object release condition is true, resulting stable state transition from force lock to bilateral control.

III. Experiment

A. Experimental setup

The proposed method is applied to the experimental setup. Fig. 7 shows the bilateral system hardware setup. It consists of two identical rotary motors as actuators. The experiment is carried out using a balloon, a rubber sponge and, an Aluminium block as the slave environment. The control software with above force lock functions is written using C language on mbed LPC1768. Table II shows the relevant parameters of the experiment.

B. Experimental Results

The experimental results are shown using two rotary motors. Therefore torque lock is presented instead of the force lock. Fig. 8a to Fig. 9 show the results of RTOB based force lock to be used with bilateral control. The Aluminium block

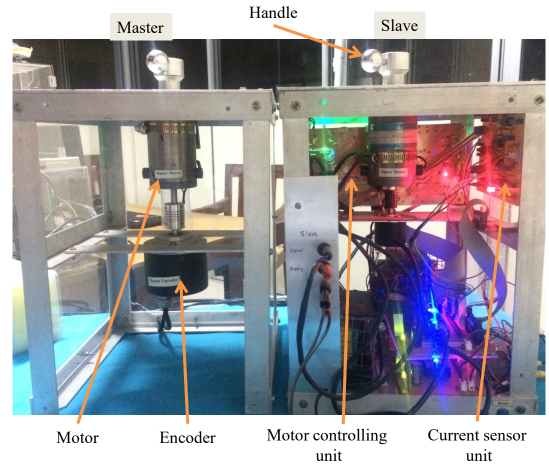


Fig. 7. Hardware setup.

TABLE II. PARAMETERS OF EXPERIMENTS.

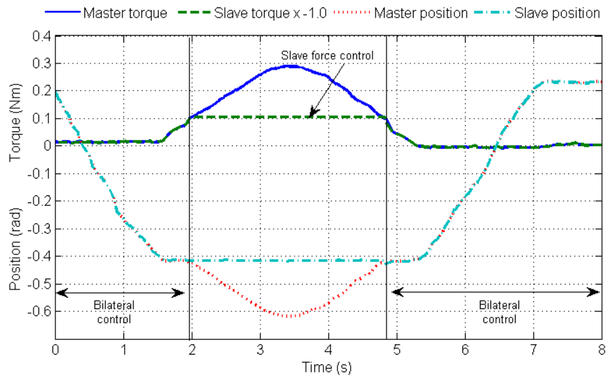
Para.	Description	Value
K_{tn}	Torque constant	$0.135Nm/A$
J_n	Nominal motor inertia	$0.00091kgm^2$
K_p	Proportional gain of bilateral controller	900.0
K_d	Derivative gain of bilateral controller	10.0
K_i	Integral gain of bilateral controller	10.0
T_{limit}	Torque limit of torque controller	$0.1Nm$
$K_{p,T}$	Proportional gain of torque controller	650.0
$K_{d,T}$	Derivative gain of torque controller	1.1
$K_{i,T}$	Integral gain of torque controller	60.0
k_{sp}	Spring coefficient of spring controller	$1.0Nm/rad$
$K_{p,sp}$	Proportional gain of spring controller	550.0
$K_{d,sp}$	Derivative gain of spring controller	10.0
$K_{i,sp}$	Integral gain of spring controller	5.0
k	vibration magnitude gain	$0.05rad$
g_{dis}	Cut-off frequency of DOB	$100.0rad/s$
g_{rec}	Cut-off frequency of RTOB	$100.0rad/s$
dt	Sampling time	150.0 μ s

is used as the slave environmental object. The slave object release condition of the lock is varied as listed in Table I. In each scenario the lock is activated when the estimated reaction torque from the slave environment $\hat{t}_s^{ext}$ exceeds or equal the pre-defined torque limit T_{limit}.

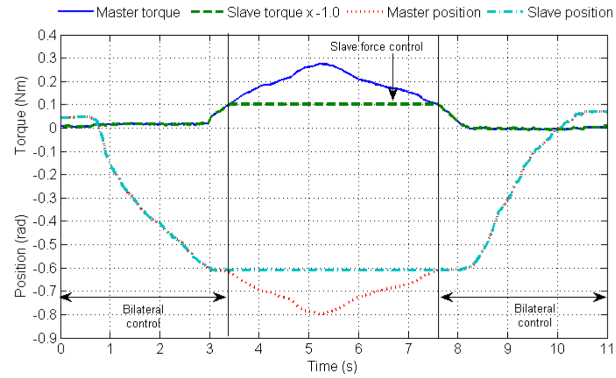
The system follows bilateral control when it is not in torque lock mode. The areas where the system follows bilateral control are marked using double arrows. When system follows bilateral control, results show that the master and the slave follow same positions. The action-reaction law is also true because reaction torque magnitudes are equal on both slave and master. The slave reaction torque response has been plotted inverted for the easiness of comparison. The limit of $0.10Nm$ is used on the slave environment object.

In Fig. 8a near $1.5s$ slave actuator touches the environmental object and master increases his holding force for better grip. The torque reaction from the slave follows master until T_{limit} is reached. By $2s$ slave reaction satisfies $(\hat{t}_s^{ext} \geq T_{limit})$ and lock is activated. The position responses during $1.5s - 2s$ are remained unchanged because slave environmental object is an Aluminium block.

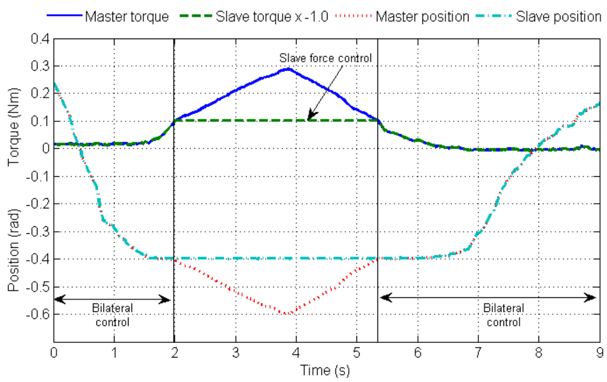
When the lock is active operator behavior does not affect the slave environmental object unless operator satisfies the release condition. During active torque lock operator tries to further press the object. The system is giving the freedom to



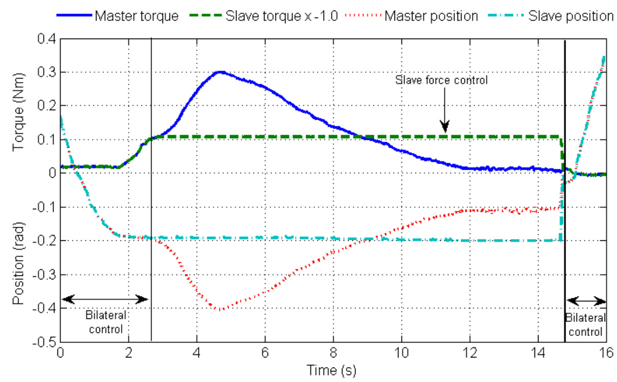
(a)



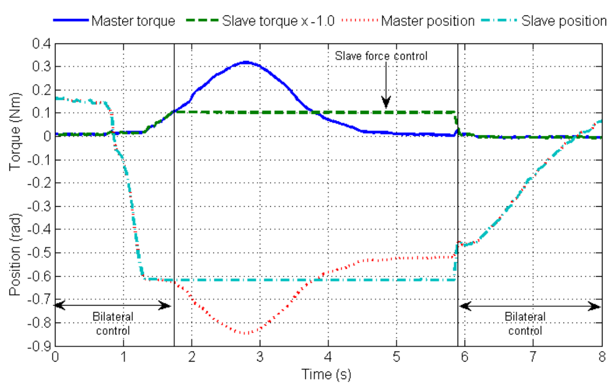
(b)



(c)



(d)



(e)

Fig. 8. In each scenario lock activation condition is $\hat{t}_{RTOB_s} \geq T_{limit}$. The lock release conditions (a). $x^s_{eq} - x_m < 0$ (b). $\hat{t}^{ext}_m < T_{limit}$ (c). $(x^s_{eq} - x_m < 0)\&(\hat{t}^{ext}_m < T_{limit})$ (d). $\hat{t}^{ext}_m < 0$ (e). $(x^s_{eq} - x_m < 0)\&(\hat{t}^{ext}_m < 0)$ should satisfied by the master operator. The system follows bilateral control when it is not in force lock mode.

operator with virtual spring effect which is produced around slave equilibrium position x^s_{eq} on the master side. In Fig. 8a from $2s$ to $4.75s$ master operator varies holding torque and the master position response follows operator applied torque. As operator reduces his holding torque master position converge towards x^s_{eq} due to spring effect. Due to the modification of spring controller by introducing T_{limit} as a reference, operator cannot release hand in the lock mode. When operator reduces holding torque beyond the T_{limit} master position response satisfies the lock release condition ($x^s_{eq} - x_m < 0$) and hence the lock is released and both master and slave follow bilateral control.

In next few paragraphs only the lock release condition will be elaborated because in each scenario lock activates whenever ($\hat{t}^{ext}_s \geq T_{limit}$) condition is true and virtual spring facilitates the operator freedom to further press his leaver towards torque increasing direction. The virtual spring also tries to equalize the master-slave positions in lock mode. In Fig. 8b lock is released when the estimated reaction of operator holding force $\hat{t}^{ext}_m$ reduces beyond the T_{limit} (i.e. $\hat{t}^{ext}_m < T_{limit}$). In this condition also operator is not allowed to free the hand during active lock.

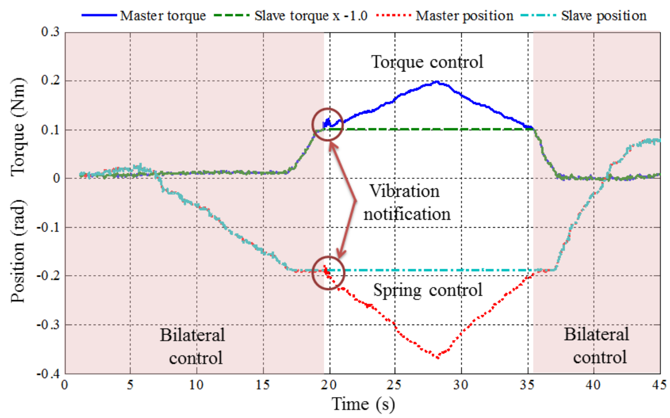


Fig. 9. Force lock result with vibration notification.

Fig. 8c shows the result of release condition corresponds to $((x^s_{eq} - x_m < 0)\&(\hat{t}^{ext}_m < T_{limit}))$. This is a combination of release conditions 1 and 2 discussed above. Results shown in Fig. 8a, 8b, 8c do not allow operator to release the hand during object is locked. Operator intention does not affect the torque lock on the slave object unless it is release condition. In these three scenarios there are no step transitions which cause system instability.

In Fig. 8d the system facilitates operator freedom to release the hand during active lock. The lock remains active until operator reverse the torque on master actuator (i.e. releases condition is $(\hat{t}^{ext}_m < 0)$. The master position response does not stabilize when it equals to slave equilibrium position $(x^s_{eq} = x_m)$ due to the introduced reference torque T_{limit}.of spring controller. It stabilizes where $(T_{limit} + T_{sp} = 0)$. The shown inequality in position responses and torque responses induce step transition from torque lock mode to bilateral motion mode. Results in Fig. 8e are also similar to Fig. 8d. In here the lock release condition is $((x^s_{eq} - x_m < 0)\&(\hat{t}^{ext}_m < 0))$.

Fig. 9 shows the results of torque lock including all functions. Both master and slave follow bilateral control nearly first $19s$. Near $19s$ the slave environment reaction reaches the predefined torque limit. Therefore torque lock is activated. The constant torque of $0.10Nm$ remains on the slave side until $36s$. When master operator satisfies $((x^s_{eq} - x_m < 0)\&(\hat{t}^{ext}_m < T_{limit}))$ the release condition lock is released. The master operator increases his holding torque during $19s - 36s$ with virtual spring. The vibration notification is presented at the time of lock engaging. The vibration or increased holding torque have not affected the torque lock on the slave side. When the torque lock is active slave actuator maintains constant position because environment is Aluminium block. The master position is changing with the master operator holding torque adjustments due to vertual spring. When the release condition satisfied by the master operator, again master and slave follow the bilateral motion. The shaded areas in Fig. 9 represent bilateral control before torque lock engage and after torque lock release.

IV. Conclusions

The delicate objects attached to slave need to handle with care during remote bilateral manipulation. In such a situation, the proposed force lock could be effectively used. The force lock passes through several states like bilateral control, force control, spring control, etc. It results on step changes and usually cause system instability during state transition. During active force lock the system violates the basic equations of the bilateral motion control. The proposed system is designed to retain the stability during state transition. The proposed locking mechanism has been exemplified for a single DOF system. When multy DOF manipulators are used during bilateral teleoperation, the locked object would be safely placed to the required position where operator needs not to worry about the force limit of the object. The proposed force lock would be successfully implemented to applications like tele-surgery where the gripped organs need to be handled with care. The lock will apply continuous force on the organ even omitting the human errors. The results verify the applicability of new concept to bilateral teleoperation.

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