

Virtual Torsional Spring Based Bilateral Control System for Soft Manipulation

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Abstract- In recent years, although there are many researches on bilateral control, there is only little research on improvement of operability. It will be so effective for operators to improve the operability of the bilateral control system. In a bilateral control system, the law of action and reaction between master system which the operator manipulates, and the slave system which has contact with the environment is realized. Objective of this research is to eliminate the chattering and to reduce the impact on human operator at contact motion and to introduce controlling force to the slave manipulator to provide more comfort at the human operator's end. In this paper, a new method of improving the operability which is based on a virtual torsional spring between master and slave system is discussed. Disturbance observer is used as the disturbance compensation tool and also to improve the system robustness. Then proposed method is applied by altering the bilateral control system. Finally the experimental results show the viability of the proposed method.

Keywords- Bilateral Control, Soft Handling, Disturbance Observer, Reaction Torque Observer, Virtual Model

I. INTRODUCTION

The prefix 'tele' from Greek origin means "at a distance" and teleoperation naturally indicates operating at a distance. Teleoperation extends the human capability to manipulate objects remotely by providing the operator with similar conditions as those at the remote location. This is achieved via installing a similar robot manipulator called the master, at the human's end that provides motion commands to the slave which is performing the actual task. [1]

The human imposes a force on the master manipulator which in turn results in a displacement that is transmitted to the slave that mimics the motion. If the slave possess a force sensor, it

can transmit or reflect back the reaction forces from the task being performed to the master, which input torque of the master, and the teleoperator is said to be controlled bilaterally.[2][3]

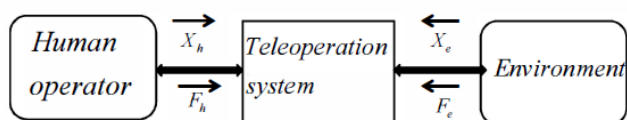


Fig.1 Broader overview of bilateral teleoperation

The principle of bilateral teleoperation is depicted in fig. I. To allow force feedback, position and/or force measurements must be made at the slave and sent back to the master. The master is provided with actuators to be able to exert forces on the user. The actuated master is also called a haptic interface where the term 'haptic' refers to the sense of touch [4]. Basically the sense of touch is made of the components: the sensation, position and the force acting on them. This information is gathered by different sensors.

Some researchers have tried to introduce added functionalities to the conventional bilateral control systems to be used where one to one control is not preferable [1]. The idea had been to implement different tool sensations virtually which can be widely used in medical surgeries. In conventional bilateral control systems where the sampling frequency is less and the encoder accuracies are low, system tends to have high level of chattering in the contact motion. One of the objectives of this research is to embed a spring feeling to the operator especially in the contact motion which reduces the chattering problem.

By incorporating the virtual spring sensation to the master-slave system, the operator can exert the controlled force to the remote object which could be felt by the master manipulator. When the slave manipulator hits an object, its impact is reflected to the master operator in the conventional bilateral control system. However by incorporating a virtual spring in between the master-slave, the impact sensation could not be felt as it is at the operator's end. In simple terms the proposed method promotes operability. This is done at the expense of the transparency [5], and it should be used in applications where one to one bilateral control is not desired. In this paper a novel concept of "soft manipulation" is introduced.

II. MODELING AND ANALYSIS

A. Virtual Torsional Spring Model

The proposed concept is built by considering a simple torsional spring, damper and two masses which are interconnected as shown in fig. 2.

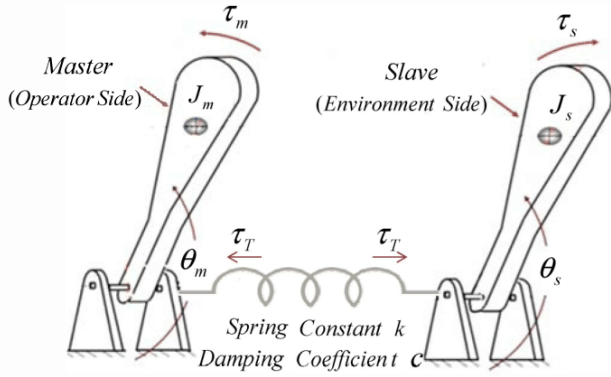


Fig.2. Analysis model of the experimental system

m and s suffixes refer to the master and slave sides. θ is the angular displacement and the τ_T is the external torque on the manipulators by the torsional spring. J refers to the inertia where k and c refer to the spring constant and the viscous coefficient of the virtual torsional spring respectively. τ_m and τ_s are the external torques acting on the given system. Practically these torques are given by “master” and “slave” motors where these two manipulators are kept away and tele-operated, equal and opposite torques are applied from the human operator and environment.

For master motor applying Newton's Law,

$$\begin{aligned} J_m \ddot{\theta}_m &= \tau_m - \tau_T \\ J_m \ddot{\theta}_m &= \tau_m - [k(\theta_m - \theta_s) + c(\dot{\theta}_m - \dot{\theta}_s)] \end{aligned} \quad (1)$$

For slave manipulator,

$$\begin{aligned} J_s \ddot{\theta}_s &= \tau_T - \tau_s \\ J_s \ddot{\theta}_s &= [k(\theta_m - \theta_s) + c(\dot{\theta}_m - \dot{\theta}_s)] - \tau_s \end{aligned} \quad (2)$$

The equations (1) and (2) can be rewritten as equations (3) and (4), to implement in the control block diagram.

For master,

$$(J_m s^2 + cs + k)\theta_m = \tau_m + (k + cs)\tau_s \quad (3)$$

For slave,

$$(J_s s^2 + cs + k)\theta_s = (k + cs)\tau_m - \tau_s \quad (4)$$

Where;

s : Laplace operator

In bilateral control, the law of action and reaction between the operator and the environment is realized. In the system the operator's action on the environment is realized by two functionally related systems (devices). The operator is in contact with one of the devices (master device), and another device (slave device) is in contact with the environment [6]. By manipulating the master device the operator defines the task to be assigned to the slave device. The master device in addition to acquiring motion data from the operator is able to exert reaction force on the operator. The slave device replicates the operation motion at the remote center, haptic interactions with the environment and transmits information of its motion and interaction force to the master device and the operator. In bilateral system there are four players: (i) operator, (ii) master side device (robot), (iii) slave side device (robot) and (iv) object to be manipulated. All of these players have their own dynamic properties. The inputs to the system are operator's force and motion and the force generated due to the interaction of the slave side and the object to be manipulated [7][8].

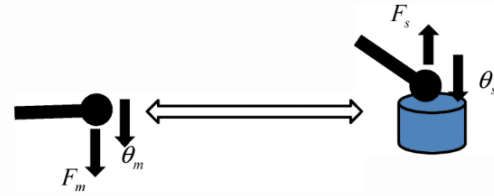


Fig.3. Basics of bilateral control

Fig.3. shows the basics of bilateral control. For bilateral control without scaling, following equations could be derived.

$$\theta_m - \theta_s = 0 \quad (5)$$

$$f_m + f_s = 0 \quad (6)$$

There are many scaling methods. Namely; position, torque, impedance and sometimes time scaling [9][6] is also used.

In ideal position control, control stiffness k should be ∞ . In bilateral control it is necessary to attain both ideal force control and position control simultaneously.

The equations (5) and (6) are transformed to (7) and (8) as accelerations.

$$\ddot{\theta}_m - \ddot{\theta}_s = 0 \quad (7)$$

$$\ddot{\theta}_m + \ddot{\theta}_s = 0 \quad (8)$$

Since disturbance observer is used as force sensor in the bilateral control, sampling time should be small enough. The relationship of force represented in (7) is called the common mode between the master and slave system. The equation (8) which represents the position relationship is called as the differential mode. This can be attributed to the sign of the equations. Therefore, it is possible to realize both force control and position control independently to the bilateral control. Equation (7) and (8) can be transformed into the following equations based on the optimal goal of bilateral control.

$$\ddot{\theta}_m - \ddot{\theta}_s = \ddot{\theta}_{com} \rightarrow 0 \quad (9)$$

$$\ddot{\theta}_m + \ddot{\theta}_s = \ddot{\theta}_{dif} \rightarrow 0 \quad (10)$$

As for the control structure, it can be clearly seen that the structure adheres to the control equations. Positions and forces are transformed and combined in the acceleration dimension. Disturbance Observer and Reaction Torque Observer are used in both master and slave as well. The equations (5) and (6) are realized by using two “master” and “slave” motors. The full control block by incorporating equation (9) and (10) is depicted in fig. 4. Here no force sensors are employed for the force sensing. Reaction torque observer [3] is used as the force sensor. Disturbance observer is used to compensate the unknown disturbances acting on the system. Further it enhances the overall robustness of the system.

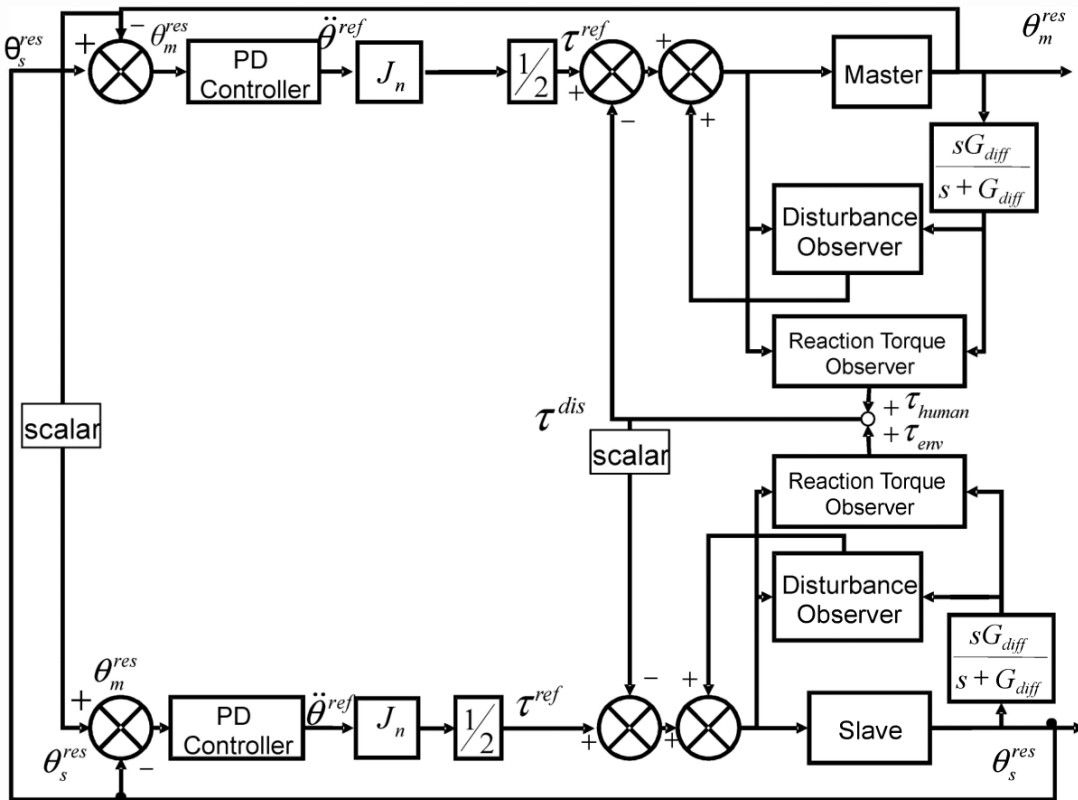


Fig.4. Block diagram of conventional bilateral control

A. Disturbance Observer

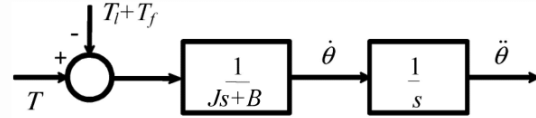


Fig. 5. Block diagram of a servo motor

When a servo motor with one degree of freedom is considered, under an ideal motor driver, a servo motor in the joint space can be represented as follows (11).

$$J\ddot{\theta} = T_m - T_l \quad (11)$$

Where;

T_m : Motor torque

T_l : Load torque

J : Motor inertia

$\ddot{\theta}$: Angular acceleration

The load torque is considered as,

$$T_l = T_{int} + T_{ext} + (T_f + B\dot{\theta}) \quad (12)$$

T_{int} the inertial torque, derived from the Lagrange motion equations, consists of inertia torque and gravity effect. T_{ext} consists of the torque external to the system. Friction term is the sum of coulomb and viscosity terms. For a high gain current controller, input current can be assumed as the reference current [10]. Therefore for a DC servo motor,

$$J\ddot{\theta} = K_t I_f - (T_{int} + T_{ext} + T_f + B\dot{\theta}) \quad (13)$$

Above equation has two parameters namely inertia and torque constant. Inertia can be changed due to the mechanical configuration of the system.

$$J = J_n + \Delta J \quad (14)$$

Similarly parameter K_t may also change.

$$K_t = K_{tn} + \Delta K_t \quad (15)$$

Where J_n and K_{tn} are nominal inertia and the nominal torque constant of the motor respectively.

Disturbance torque T_{dis} is represented as,

$$T_{dis} = T_l + \Delta J\ddot{\theta} - \Delta K_t I_{ref} \quad (16)$$

Dynamic equation yields,

$$(J_n + \Delta J)\ddot{\theta} = (K_{tn} + \Delta K_t)I_{ref} - T_l \quad (17)$$

By rearranging,

$$J_n\ddot{\theta} = K_{tn}I_{ref} - T_{dis} \quad (18)$$

Thus T_{dis} can be calculated as follows.

$$T_{dis} = K_{tn}I_a^{ref} - J_n\ddot{\theta} \quad (19)$$

In actual application, the disturbance observer is effective not only for the disturbance compensation but also for the reaction torque estimation. That is, the disturbance observer is able to estimate the reaction torque without using a torque sensor by identifying the internal disturbance of the system. The transmission of force sensation by bilateral control is based on the action and reaction relationship. The disturbance observer calculates and estimates the reaction torque as quickly as possible by increasing the cut-off frequency [11]. The block diagram of the reaction torque observer is shown in fig. 7.

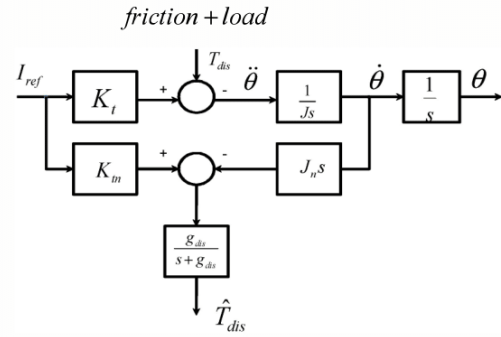


Fig. 6. Disturbance Observer block diagram

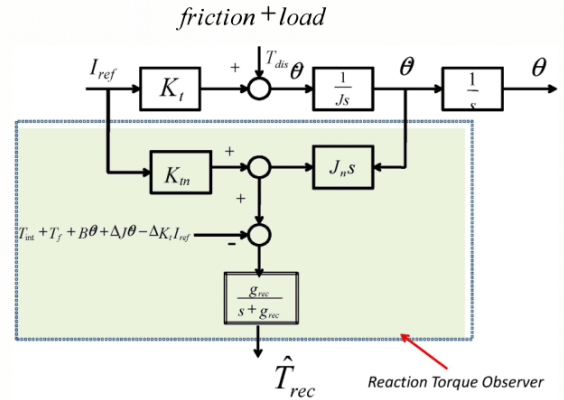


Fig. 7. Reaction Torque Observer block diagram

IV. CONTROL SYSTEM

The proposed method of soft handling basically manipulates the positions of master and slave systems. Equations (3) and (4) are arranged to obtain the relationship between master and slave systems. Equation (5) and (6) is replaced by equations (3) and (4) and implemented in block diagram shown in fig 8. Two motors are fed with position of other motor and given the feedback of their own position. The error is fed to the PD Controller. Torques's of two motors are engaged with the torsional spring action and only at standstill the torques are equal and opposite. When k goes to ∞ , the virtual spring becomes a rigid link and conventional bilateral control holds.

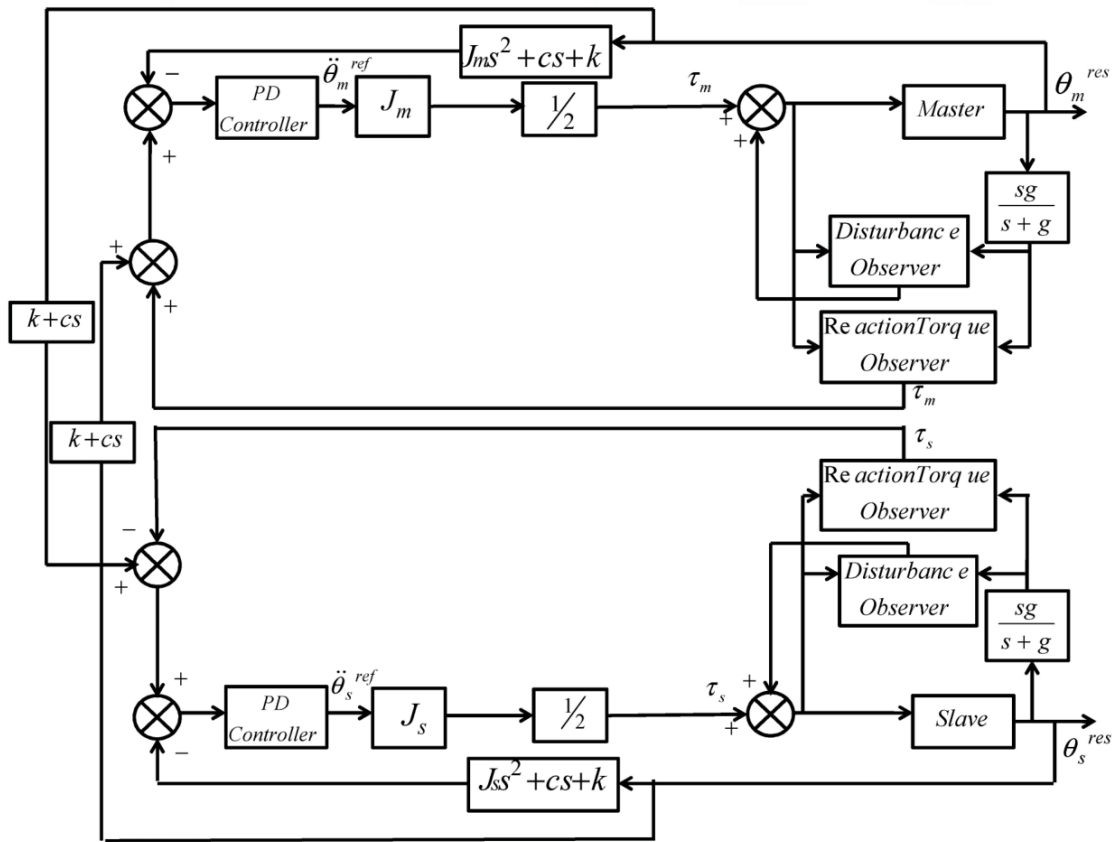


Fig.8. Modified control block diagram of bilateral control system

V. METHODOLOGY

A. Hardware Experimental System

In order to demonstrate and simulate the functionality of soft manipulation of a bilateral system, here we used two hardware manipulators consist with master and slave units coupled with two brushed DC motors manufactured by Electrocraft Inc. Fig.9. shows the arrangement of hardware experimental platform.

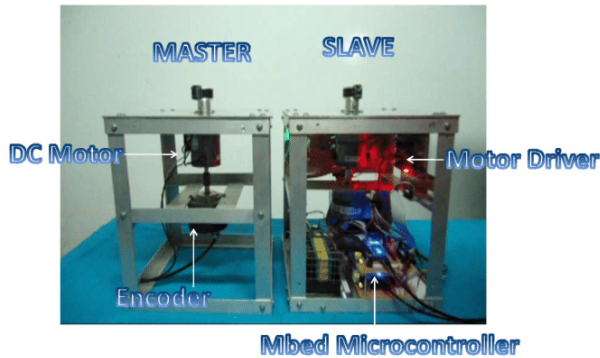


Fig.9. Hardware experimental systems

In this platform it has two PWM driven motor drivers constructed with two DRV8432 direct PWM driven drivers. Basically each unit is controlled by one IC which can carry up to 14A with 24A peak load. PWM signal to both drivers are given by *mbed NXPLPC1768* microcontroller. Position sensing is done by two encoders coupled with master and slave manipulators, which are having 5000ppr and 2500ppr respectively.

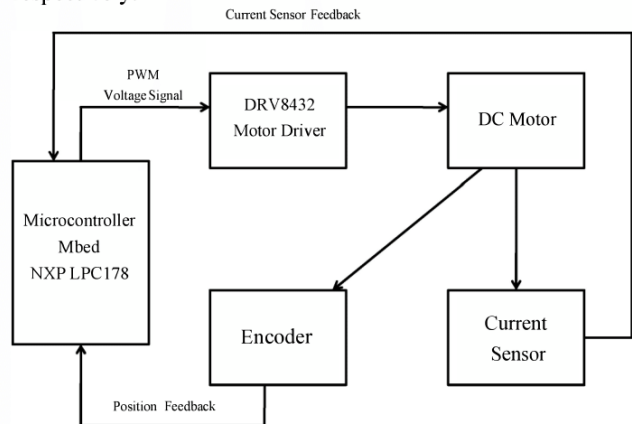


Fig.10. Hardware Functional block diagram

Current Sensing is done using Hall Effect based sensor (ACS712) which is having a frequency response of 200 kHz. The output of each current sensor is fed into a differential amplifier stage and ranged up to 3.3V from 0V for both directions. Hardware arrangement for one side of the platform can be illustrated as Fig. 10. Current is sensed through the inbuilt A/D converter supplied in the *mbed NXPLPC1768* microcontroller. Current sensing is invoked every 150 μ s.

B. Software Experimental System

The *mbed NXPLPC1768* microcontroller used in this research has limited resources. To optimally use the limited resources, Real Time Operating System (RTOS) is incorporated. Motor torques is determined by measuring the current through motors. Outputs of two current sensors are amplified to obtain a 0-3.3V signal. Two directions of rotation for two motors give four current output signals which are fed to four Analog input pins of the microcontroller. The sensed current is continuously averaged to attain a more accurate output and written in a thread in RTOS.

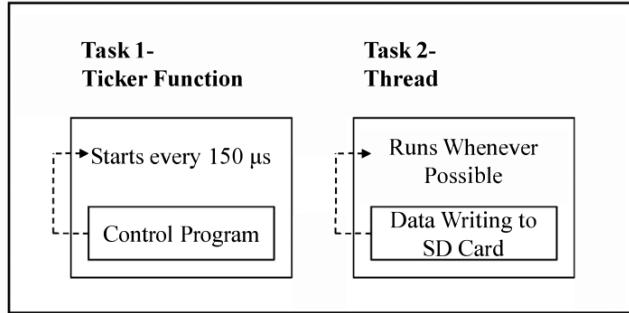


Fig.11. Structure of real time operating system

VI. RESULTS

In this section the law of action and reaction was realized by the bilateral control system with limited resources available of a microcontroller. All computations are written in C language under real time operating system (RTOS) with a sampling time of 150 μ s as shown in fig 11. Parameters used in the experiment are shown in table II. Time critical main control program is invoked every 150 μ s, while the data writing task is given the lowest priority. Table I shows the priority and speed specific parameters of the hardware and the software setup.

TABLE I
Frequencies used in the system

Parameter	Description	Max. Possible	Used in study
dt	Sampling time	150 μ s	150 μ s
A/D Conversion frequency	Same as Sampling rate	200kHz	5kHz
PWM Frequency	Considerably higher than sampling frequency	1MHz	100kHz
Driver Operating Frequency	Used at the PWM frequency	500kHz	100kHz

TABLE II
Experimental parameters

Parameters	Symbol	Value	Units
Motor inertia	J_n	0.268	Kgcm ²
Torque coefficient	K_t	13.5	Ncm/A
Proportional constant	K_p	0.001	Rad/s
Integral constant	K_i	0.0	Rad/s
Derivative constant	K_d	0.00001	Rad/s
Cut-off frequency of low pass filter	g_{dis}	1.0	Hz

A. Bilateral Controlling with soft handling

Experiment is performed with the setup shown in Fig 9. A human operates the master manipulator and the slave manipulator was allowed to run freely. Then the slave manipulator is contacted with a hard object to demonstrate the contact motion. Fig. 12 (a) and (b) shows the position and torque responses of each manipulator in conventional bilateral control. As shown in equations (5) and (6), it is evident that the positions of master and slave manipulators are coinciding while the torques are equal and opposite. Fig. 12 (c) and (d) shows the position and torque responses of each manipulator with virtual torsional spring action engaged. According to equations (1) and (2), it is seen that at contact motion positions are not followed one to one, but forces are matched as in conventional bilateral control.

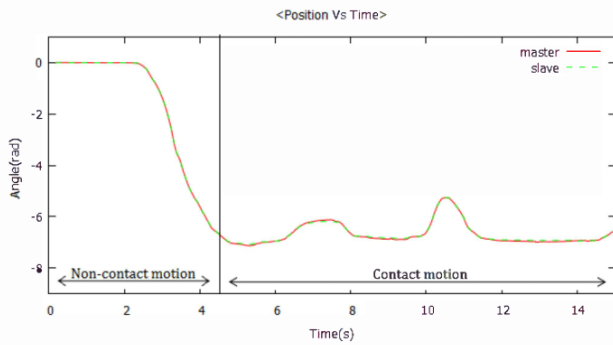


Fig. 12(a) Position response in conventional bilateral control

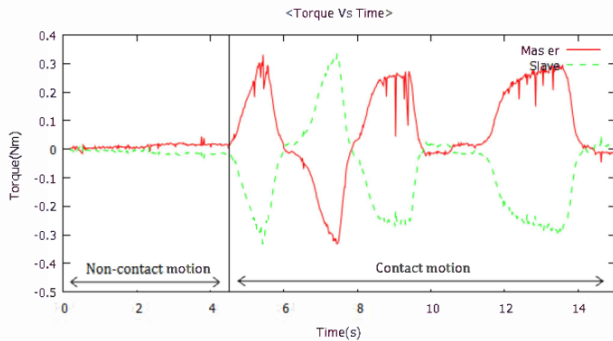


Fig. 12(b) Force response in conventional bilateral control

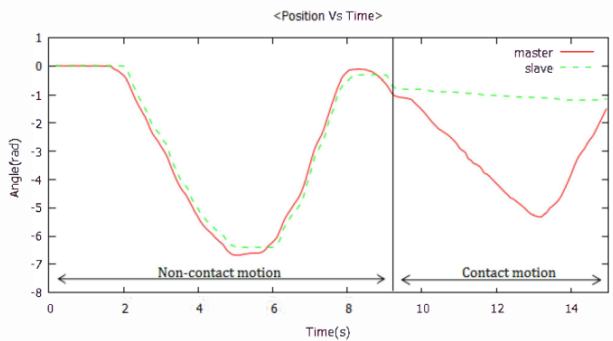


Fig. 12(c) Position response with virtual spring action

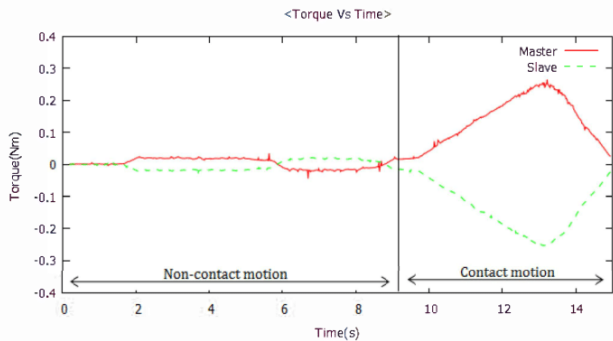


Fig. 12(d) Force response with virtual spring action

While the slave manipulator is contacted and does not move, master manipulator can be moved further, exhibiting spring action. At the meantime the increasing reaction force at the slave end is felt at the master end.

VII. CONCLUSIONS

In this paper virtual torsional spring based bilateral control was proposed and modeling, control implementation was shown. Position servoing and torque servoing was accomplished in parallel as for the results. Experiments are carried out for the proposed method to confirm its validity. Position tracking between master and slave manipulators and the law of action and reaction were achieved in each case to validate the bilateral control.

VIII. ACKNOWLEDGMENTS

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