Bilateral Control interacting with a Virtual Model and Environment

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Abstract **– Bilateral Control enables the operator to be placed away from the working environment. Slave manipulator usually works in a remote site or in a hazardous environment. Master operator is sensing the environment through the slave manipulator. Usually if scaling is not used, master operator could feel the slave environment as it is. If the master operator should feel a feeling other than that is coming from the slave, a virtual model can be used to modify the feeling. Even though this concept can be used in many industrial applications, bilateral forceps robot is used to prove its applicability. If bilateral control is used in a surgery, ideally doctor should feel the feeling of the body tissue and the reaction force from the specialized tool. Virtual spring acting at the end of the forceps is implemented to the bilateral control so that operator at the master side could feel the spring feeling together with the environment. Reaction torque observer is used as the method of measuring the reaction force. Virtual model is inserted in-between the disturbance observer inputs so that the virtual model together with the environment is reflected in the output of the reaction torque observer.**

I. INTRODUCTION

Motion control is a wide area that came to light with the automation. Bilateral control is also coming under the broad subject of motion control. Sensing an environment remotely is the main idea of bilateral control.

A. *Bilateral control*

As the word “bilateral” literally means, bilateral control is about controlling bilaterally. Slave side is controlled through the position and force information from the master side and master side is controlled by the position and force information from the slave side. Bilateral control can be broadly categorized according to the scope of applications. First application is remote sensing. If the environment to be sensed is placed at a remote location, communication is usually done with the communication networks. Bilateral control is also used in hazardous environments where human operators are inaccessible. Third application area involves scaling the environment. Micro-Macro or Macro-Micro applications are examples for this.

Usually if scaling is not used, slave environment could be directly sensed through the master manipulator. However there are applications where, master operator should feel differently than the sensation coming from the slave environment. What the master operator should feel would be the slave environment added with a virtual model. This idea is depicted in the Fig. 1.

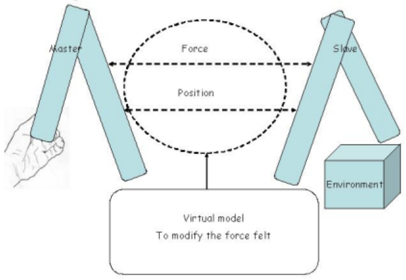

Fig. 1. Virtual model with bilateral control

By changing the virtual model, various sensations could be developed. In this paper we apply this idea for a bilateral forceps robot.

B. *Minimally Invasive Surgery*

Minimally Invasive Surgery (MIS) is sometimes called minimal-access or "keyhole" surgery. MIS is one of the exciting recent developments in medicine. A minimally invasive procedure is performed via a small opening instead of a long incision. Usually a small camera called a laparoscope is inserted to guide the surgeon. A long surgical tool is inserted through the incision. This tool is remotely operated by the surgeon. Remote operating has definite advantage as the surgeon has to watch the monitor while doing the surgery. Master slave systems “Da Vinci and Zeus” are examples for MIS. Main advantages of MIS include less healing time, less risks of infections and minimum blood loss.

However MIS has a major disadvantage. When the surgeon performs the operation through the surgical tool, he lacks the tactile information. To eliminate this problem, bilateral control with tactile feedback has been proposed by several researchers. W. Iida *et al.* [1] of our laboratory have proposed a forceps robot which can transmit tactile sensation to the master operator.

When special surgical instruments are used the feeling that the surgeon feels is the addition of reaction force from the environment and the tool impedance itself.

Skilled operators are very sensitive to the tools that they are used to. Surgeons are used to feel the tool reaction force as well. Following figure depicts such a specialized surgical forceps used to tie sutures. A function of a spring is embedded in the construction.

Fig. 2. Surgical tool

These specialized tools are often expensive. However lots of surgical instruments carry similarities at the tool end and some structural differences at the gripper. Therefore it is a good idea if the expensive tool can be eliminated with a virtual tool. With the virtual tool, surgeon should be able to sense the actual tool feeling together with the reaction force from the body tissue. This idea is depicted in the following figure.

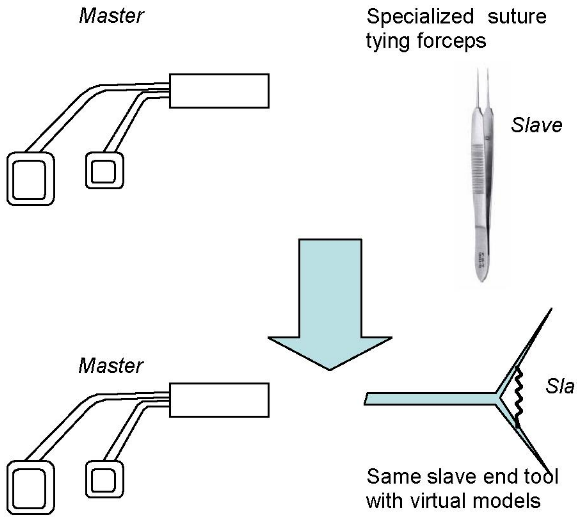

Fig. 3. Virtual tool

In other words when the end tool is similar, one end tool can be used in MIS. On the master side, varies tool sensations can be recreated, by having a virtual tool model. This idea was proposed by us [11]. However, virtual model used is acting as a reference value generator to the master side manipulator. This model can be used as a virtual model at the master side. Therefore master and slave force responses are different. However in this paper, virtual model is not inserted only for the master side or to the slave side. But it is considered as a virtual model for the whole system. Therefore force responses of this study should be almost the same. This idea can be used in many industrial applications. In this paper we have used a bilateral forceps robot to show applicability of this concept.

II. BILATERAL CONTROL

In this section bilateral control is introduced. Fig.4. shows the basic structure.

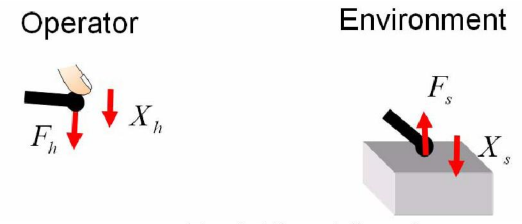

Fig. 4. Bilateral Control

Position and force information is transmitted from the slave side to the master side and master side to the slave side as well. Environment reaction is recreated in the master side. Master's operating intension is also transmitted to the slave side so that slave starts to move according to the master. If human operator exerts Fh force at the master side, and the manipulator moves by X_h, then the impedance of the master side is Z_m. This can be shown by the following equation.

$$X_h = \frac{1}{Z_m} F_h \tag{1}$$

Similarly, slave side reaction can also be shown by the following equation.

$$F_s = -Z_e X_s \tag{2}$$

Ideally, position of master and slave should be equal. Addition of forces at master and slave manipulators should be zero.

$$X_h - X_s = 0 \tag{3}$$

$$F_h + F_s = 0 \tag{4}$$

However, in applications where master and slave are different, position and force scaling may be used. Following figure depicts the basic block diagram of bilateral control. Function of the disturbance observer and the reaction force observer will be discussed in the next section. For this diagram it is assumed master and slave are driven by identical linear motors.

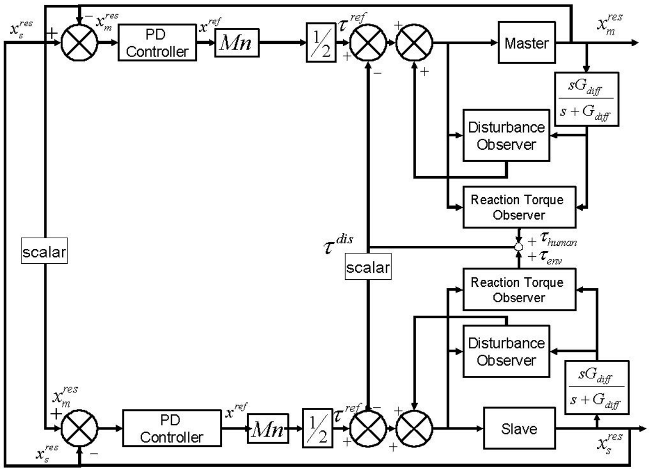

Fig. 5. Bilateral Model

If one to one response is expected from master and slave, scales are set to 1.

III. MODELING

Following figure depicts a slave manipulator. A virtual model is expected to be inserted in between the jaws.

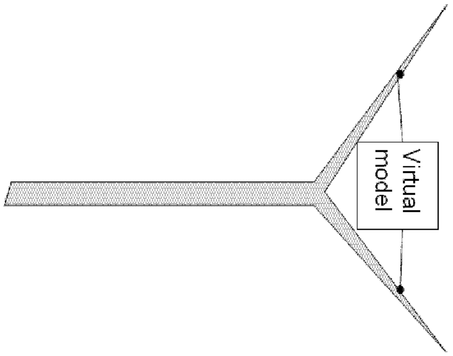

Fig. 6. Slave Manipulator with Virtual Model

Simple spring damper model is used for this experiment. Therefore master operator should feel the spring as well as the reaction force from the environment. Spring is modeled with a spring damper model depicted in Fig 7.

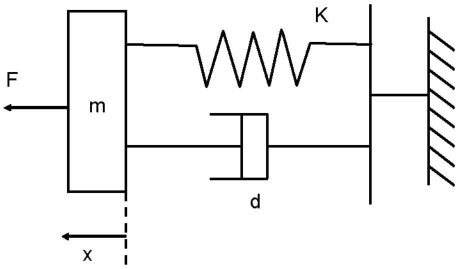

Fig.7. Virtual Spring Damper Model

Dynamics of the spring damper model is,

$$F = m\ddot{x} + d\dot{x} + kx \tag{5}$$

Where; m : Normal mass
d : Damping coefficient
k : Spring constant

In Laplace domain

$$F(s) = \left[ms^2 + ds + k\right]X(s) \tag{6}$$

Fig 8. depicts a linear motor in control blocks. Upper dotted line depicts the environmental load acting on the linear motor. Similarly the lower dotted line depicts how the virtual model acts on the linear motor..

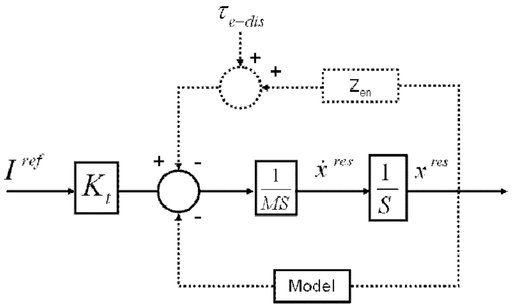

Fig. 8. Environment load and virtual model

Equation 6 is exerted to the bilateral control system is represented by Fig.9. In Fig.9 "model" represents the transfer function represented by equation (6).

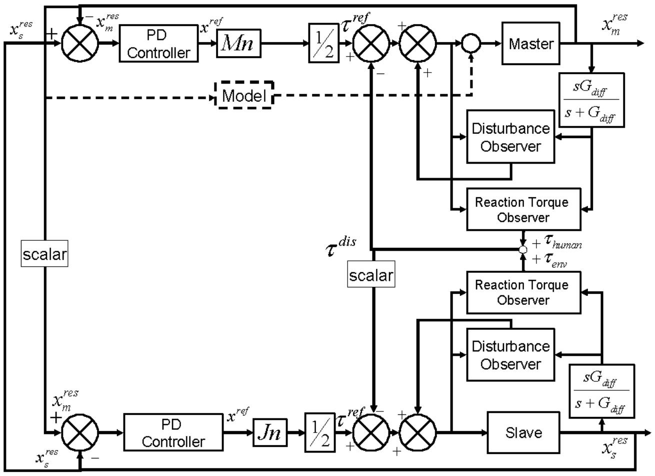

Fig. 9. Master model with Bilateral Control

IV. DISTURBANCE OBSERVER WITH VIRTUAL MODEL

Disturbance observer proposed by [7],[10] Ohnishi *et al.* was used to cancel the disturbance and to record the torque of the linear motor. This method is cost effective than having a torque recorder and it produces more reliable results. Fig.10 shows the typical arrangement of the disturbance observer. F_{dis} is the estimated disturbance. Disturbance observer is extended to calculate the operating torque.

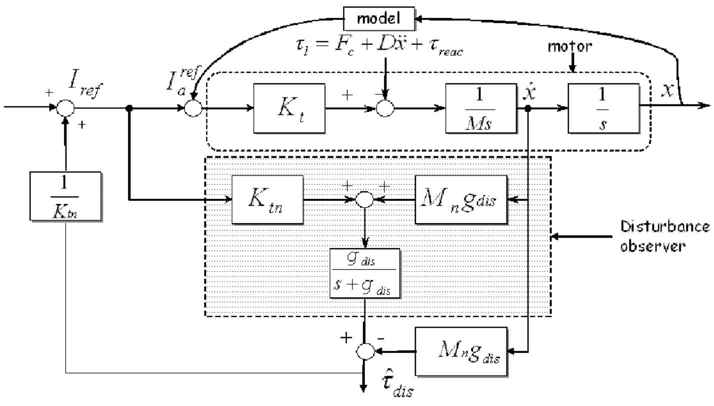

Fig. 10. Disturbance Observer

The disturbance observer could identify the total mechanical load torque and the effect of parameter change. In other words, the identification of disturbance torque is essential for motion control robustness to realize various applications.

Following section analyses an acceleration controller using a disturbance observer. Disturbance observer is designed to cancel the disturbance torque as quickly as possible. The estimated disturbance torque is obtained from the velocity response $\dot{x}^{res}$ and the current reference I^{ref} as shown in Fig.10. Virtual model is input between disturbance observer inputs. Model output as depicted in (6) can not be input as a force since that point lies within the motor. Therefore force output of the model is transformed to the current dimension by dividing k_t. The disturbance observer output force τ_{dis} is represented as follows.

$$\begin{aligned}\tau_{dis} &= (M - M_n)\ddot{x}^{res} + (K_{tn} - K_t)I^{ref} \\ &\quad + F_c + D\dot{x}^{res} + \tau_{reac} + \tau \\ &= \Delta M\ddot{x}^{res} + \Delta K_t I^{ref} + \tau_l + \tau \qquad (7)\end{aligned}$$

Where;

$$\Delta M = M - M_n \qquad (8)$$

$$\Delta K_t = K_t - K_{tn} \qquad (9)$$

$$\tau_l = F_c + D\dot{x}^{res} + T_{reac} \qquad (10)$$

$$\tau = \frac{F}{k_t} \qquad (11)$$

F_c : Coulomb friction
$D\dot{x}^{res}$: Viscous friction
ΔM : Self-Mass variation
ΔKt : Variation of force coefficient
τ_l : Load (force)
τ : Input from the virtual model

In (7), the first term is the torque variation due to the self-mass variation. The second term is force variation due to the variation of the force coefficient. The third term and the fourth term denote the coulomb and the viscous friction respectively. The next term is the reaction torque caused by external force. Final term represents the virtual model.

Equation (12) shows that the disturbance force and virtual forces are estimated through the first-order low-pass filter.

$$\hat{\tau}_{dis} = \frac{g_{dis}}{s + g_{dis}}\tau_{dis} \qquad (12)$$

Where g_{dis} denotes the cut-off frequency of the low-pass filter. The force estimated by (12) is used for a realization of robust motion control.

V. CONSTRUCTION

A. Linear Motor

Linear motor is similar to the conventional rotary motor with one exception. Here the response is in the linear direction.

Dynamic equation for the linear motor can be described by the following equation.

$$f = m\ddot{x} + d\dot{x} \qquad (13)$$

Where;

f: force
m: nominal mass
d: viscous friction of the linear motor.

$$k_t i^{ref} = f \qquad (14)$$

Where k_t is the force constant of the linear motor.

Table I
Specifications of linear motor assembly.

Maximum force	30N
Current	0.5A
Resolution	1μm
Physical weight	340g

B. Forceps Robot

Forceps robot is used for this experiment. Following figures 11, 12 depict the experimental setup of the forceps robot.

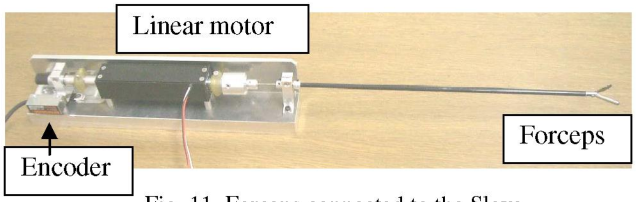

Fig. 11. Forceps connected to the Slave

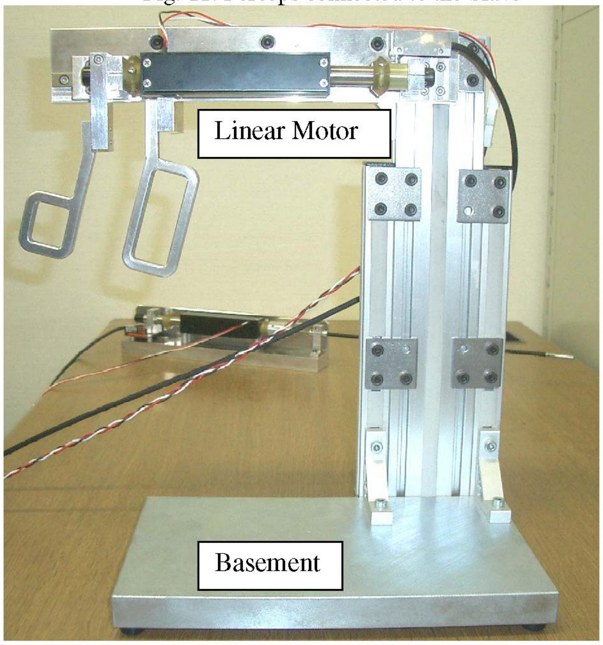

Fig. 12. Master Manipulator

VI. EXPERIMENT

The forceps robot depicted in Fig.11 was used for the experiment. Human operator directly manipulates the master system. At the end of the forceps, spongy material is kept for measurements. Initially, readings were taken without the virtual spring model. Then experiment is carried out with the virtual spring model. Same spongy material is sensed through the embedded virtual model.

Following parameters were used for the experiment.

Table II

Experiment parameters	
K_p Position gain	9000
K_v Velocity gain	200
K_f Force gain	1
K_{tn} Force coefficient	22
k Spring constant	1000
b Damping coefficient	0.01
M_n Nominal mass	0.16
St Sampling time (s)	0.0001

VII. EXPERIMENT RESULTS

Fig. 13 depicts the results when virtual model is in action with the bilateral control. The force is sensed through the master manipulator. Master manipulator was moved so that the jaws are open, then the master grippers are released to demonstrate the virtual model. This is repeated three times. When master manipulator moved virtual model could be sensed at the gripper.

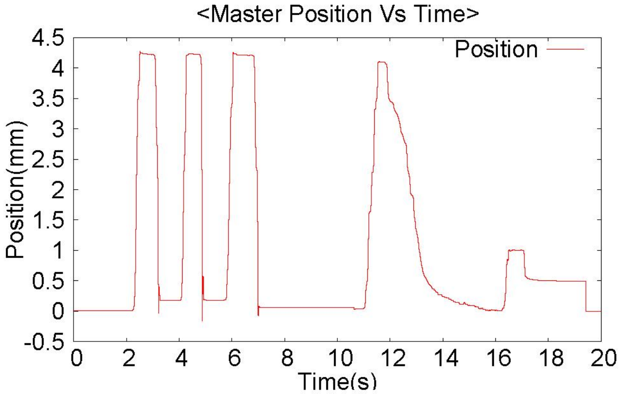

Fig.13a Master Position Response

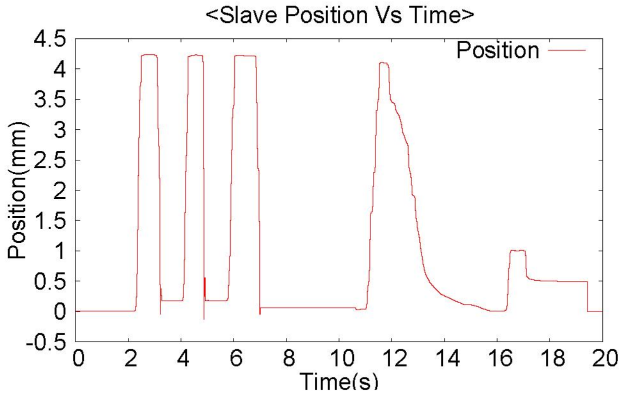

Fig.13b Slave Position Response

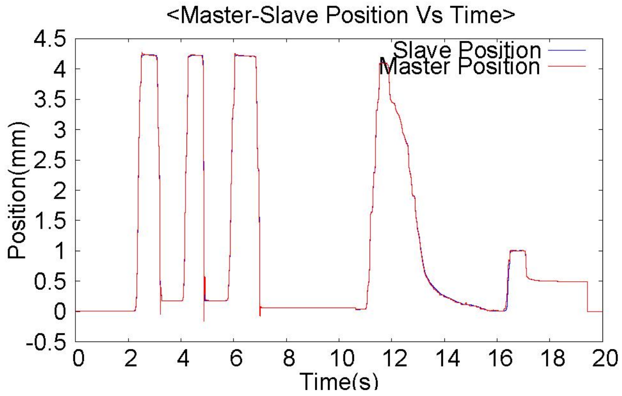

Fig.13c Master-Slave position responses together

First three variations correspond to the press and release repetitions without the slave load. Next variation corresponds to the spongy material kept at the slave end. Position responses are almost the same. Fig. 13c shows the perfectly matched position responses together.

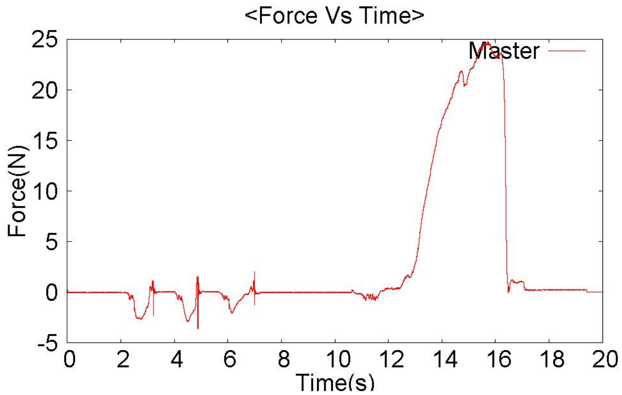

Fig.13d Master Force Response

Master and slave force responses are almost the same except the sign. This is due to the sign convention adopted based on the law of action and reaction (6).

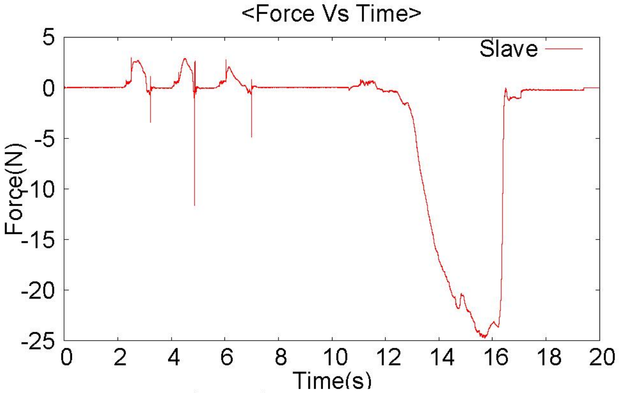

Fig.13e Slave Force Response

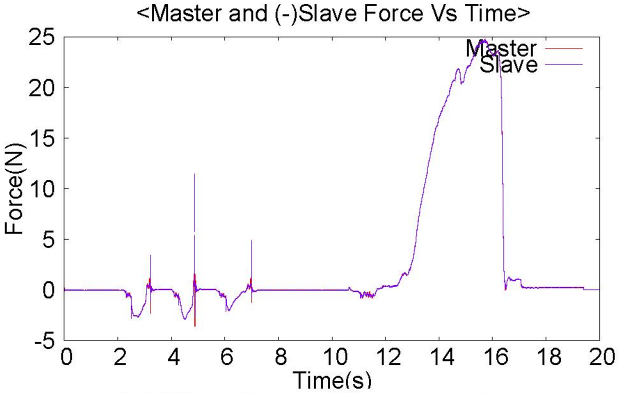

Fig.13f Master Slave Force Responses together

Fig. 13f shows a perfect match of force responses as well. Vivid sensation could be transferred from the slave side to the master side. If the virtual force is high, actual environment could not be sensed properly. Therefore force effect of the virtual model is kept small when compared to the actual environmental forces. This can be seen from the force responses. First three variations without the slave load is small compared to the force with the environment.

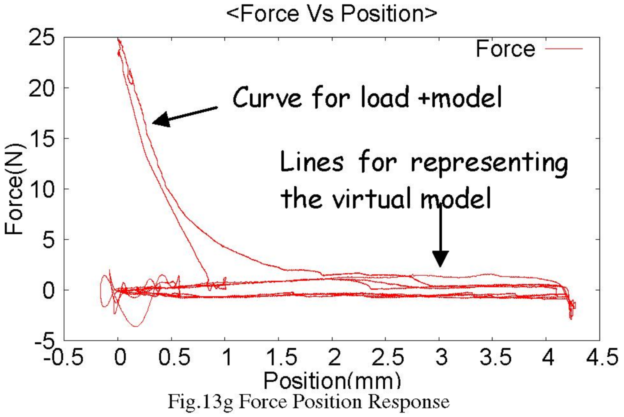

Fig.13g Force Position Response

Fig. 13g depicts the Force position variation. It shows the properties of the environment together with the virtual model. From the above graph, it could be roughly identified three lines making small angle with the x axis. Those three lines correspond to the first three variations without the slave load. Angle represents the virtual model. Curve represents the properties of the environment load together with the virtual model. Nonlinear properties of the environment could also be visible.

VIII. CONCLUSION

In this paper, a Virtual model was proposed specially for Minimally Invasive Surgery. By changing the model, Surgeon can feel the sensation of the tool together with the reaction force. Virtual model is applied between the inputs to the disturbance observer. Disturbance observer could estimate disturbance forces, load together with the virtual model.

Experiment was carried out to validate the proposal. System behaved as if an actual spring is there. Master and slave position-force responses turned out to be the same. Virtual model is acting similarly for master and slave systems. This concept can also be extended for other applications as well.

IX. REFERENCES

[1] Seiichiro Katsura, Yuichi Matsumoto, Kouhei Ohnishi ; Realization of "Law of Action and Reaction" by Multilateral Control, Transactions on Industrial Electronics, vol. 52, No. 5, October 2005.

[2] Iida, W.; Ohnishi, K.; *Reproducibility and operationality in bilateral teleoperation* Advanced Motion Control, 2004. AMC '04. The 8th IEEE International Workshop on 25-28 March 2004 Page(s):217 – 222.

[3] Tsuji, T.; Ohnishi, K.; *Position/force scaling of function-based bilateral control system,* Industrial Technology, 2004. IEEE ICIT '04. 2004 IEEE International Conference on Volume 1, 8-10 Dec. 2004 Page(s):96 - 101 Vol. 1.

[4] Y.Nishioka, K.Ohnishi, *Hybrid Control of Position and Force for Bilateral System*, The 29th Annual Conference of the IEEE Industrial Electronics Society IECON '03-ROANOKE pp. 1349-1354 , November, 2003.

[5] K.Kaneko, H.Tokashiki, K. Tanie, K.Komoria, *Impedance Shaping based on Force Feedback Bilateral Control in Macro-Micro Teleoperation System*, Proceedings of the 1997 IEEE Intl. Conference on Robotics and Automation Albuquerqur, New Mexico- April 1997, pp.710-71.

[6] K. Ohnishi, N. Matsui, Y. Hori, "Estimation, Identification and Sensorless Control in Motion Control System," *Proceedings of the IEEE*, Vol.82, No.8, pp.1253-1265, August 1994.

[7] K.Ohnishi, M. Shibata, T. Murakami, "Motion Control for Advanced Mechatronics," *IEEE/ASME Transactions on Mechatronics*, Vol. 1, No.1, pp.56-57, March 1996.

[8] T. Shimono, S. Katsura, K.Ohnishi, "Improvement of Operationality for Bilateral Control based on Nominal Mass Design in Disturbance Observer," in *Proc. IEEE Int. Conf. IECON 2005.*

[9] T.Itoh, K.Kosuge, T.Fukuda, *"Human-Machine Cooperative Telemanipulation with Motion and Force Scaling Using Task-Oriented Virtual Tool Dynamics,"* IEEE Transactions on Robotics and Automation, Vol.16, No.5, October 2000, pp.505-516.

[10] K. Ohnishi, K. Miyachi: "Torque-Speed Regulation of DC Motor Based on Load Torque Estimation," IEEJ International Power Electronics Conference, IPEC-TOKYO, Vol. 2, pp.1209-1216, 1983

[11] A M Harsha S Abeykoon, K.Ohnishi, "Realization of Virtual Master Manipulator" in *Proc. IEEE Int. Conf. INDIN 2006.*