Realization of Virtual Slave Model of a Forceps Robot Using Bilateral Control

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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. Bilateral control can also be used in surgeries. Usually doctors are very sensitive to the tactile sensation they feel through medical tools. If bilateral control is used in surgery, ideally doctor should feel the feeling of the body tissue and the reaction force from the specialized tool. In this paper bilateral control is implemented for a forceps robot. Virtual spring acting on 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.**

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.

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 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] has 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.

$$\textit{Surgeon feels} = \underset{\textit{From the surgical environment}}{\textit{Reaction force}} + \underset{\textit{reaction}}{\textit{Operating tool}} \quad (1)$$

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 to the system.

Fig. 1. 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.

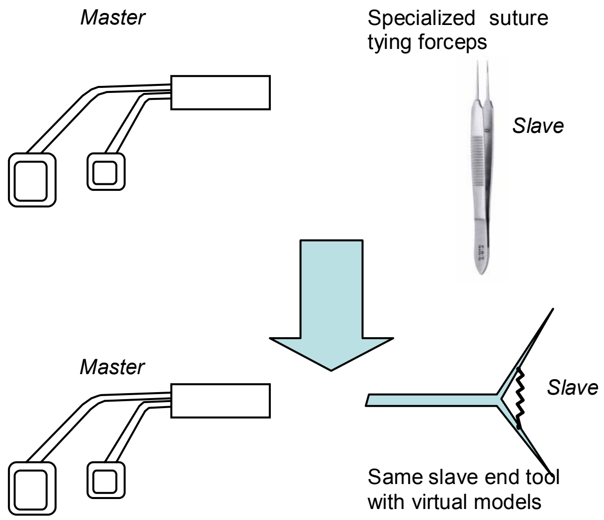

Fig. 2 Virtual tool

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 paper proposes the above idea to be used in the MIS environment.

II. BILATERAL CONTROL

In this section bilateral control is introduced. Fig 3.shows the basic structure.

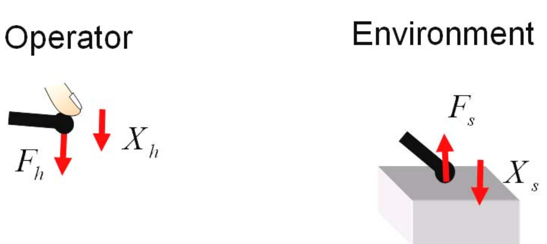

Fig 3. Bilateral Control

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. Masters 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.

$$X_h = \frac{1}{Z_m} F_h \tag{2}$$

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

$$F_s = -Z_e X_s \tag{3}$$

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

$$X_h - X_s = 0 \tag{4}$$

$$F_h + F_s = 0 \tag{5}$$

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.

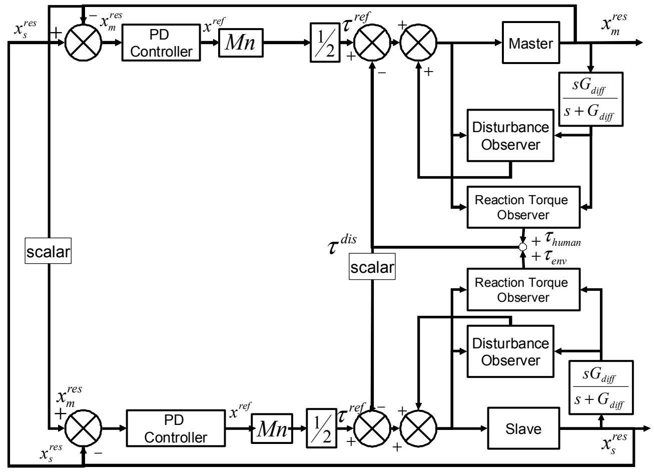

Fig. 4. Bilateral Model

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

III. DISTURBANCE OBSERVER

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.5 shows the typical arrangement of the disturbance observer. F_{dis} is the estimated disturbance. Disturbance observer is extended to calculate the operating torque.

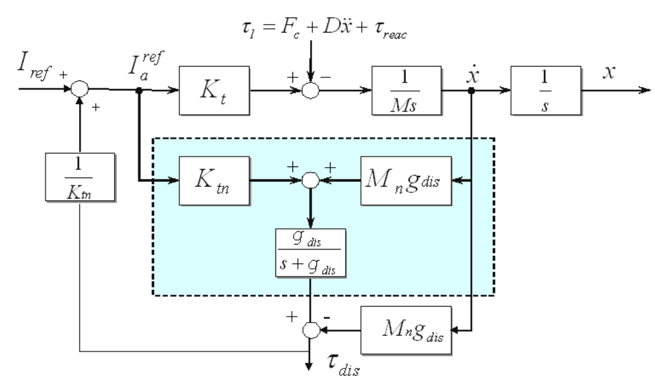

Fig. 5. Disturbance Observer

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.5.The disturbance torque τ_{dis} is represented as follows.

$$\tau_{dis} = (M - M_n)\ddot{x}^{res} + (K_{tn} - K_t)I^{ref} + F_c + D\dot{x}^{res} + \tau_{reac} \quad (6)$$

$$= \Delta M\ddot{x}^{res} + \Delta K_t I^{ref} + \tau_l \quad (7)$$

where

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

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

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

F_c	: Coulomb friction
$D\dot{x}^{res}$	: Viscous friction
ΔM	: Self-inertia variation
ΔKt	: Variation of torque coefficient
τ_l	: Load torque

In (6), the first term is the torque variation due to the self-inertia variation. The second term is torque variation due to the variation of the torque coefficient. The third term and the fourth term denote the coulomb and the viscous friction respectively. The last term is the reaction torque caused by external torque.

Equation (11) shows that the disturbance torque is estimated through the first-order low-pass filter.

$$\tau_{dis} = \frac{g_{dis}}{s + g_{dis}} \tau_{dis} \quad (11)$$

Where g_{dis} denotes the cut-off frequency of the low-pass filter. The disturbance torque estimated by (11) is used for a realization of robust motion control.

IV MODELING

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

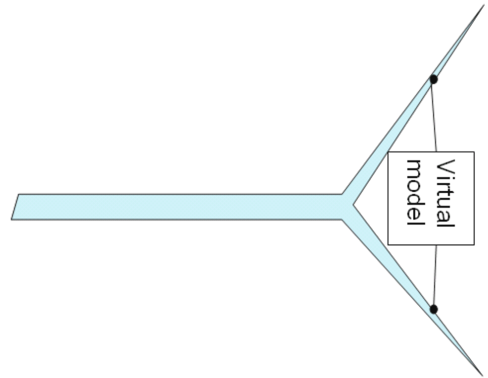

Fig 6. Slave Manipulator with Virtual Model

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 8.

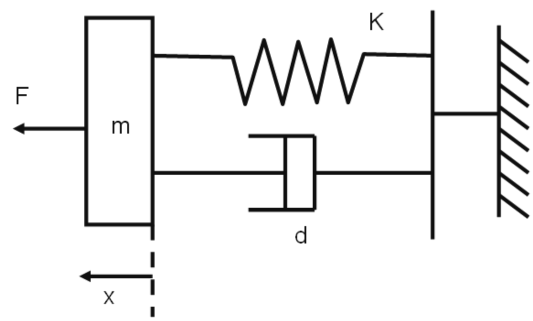

Fig.7. Virtual Spring Damper Model

Dynamics of the spring damper model is

$$F = m\ddot{x} + d\dot{x} + kx \quad (12)$$

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

In Laplace domain

$$F(s) = \left[ms^2 + ds + k\right]X(s) \quad (13)$$

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.

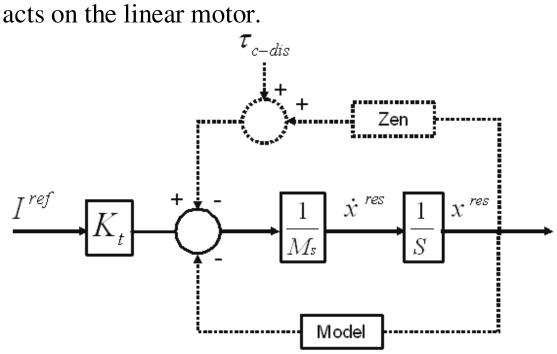

Fig. 8. Environment load and virtual model

Equation 13 is exerted to the bilateral control system. This is represented by Fig.9. In Fig.9 "model" represents the transfer function represented by equation 13.

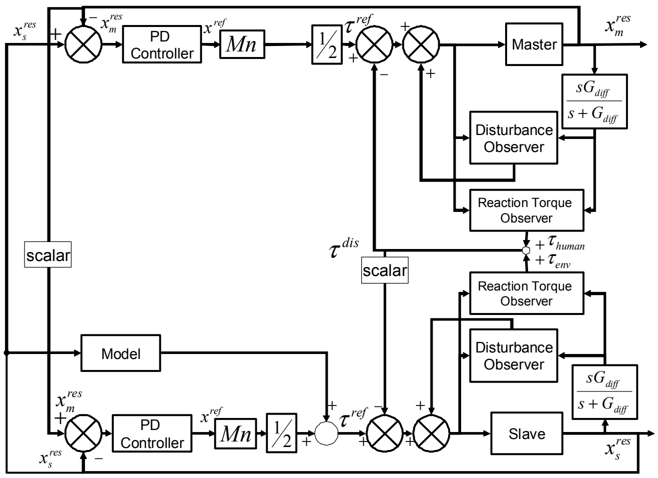

Fig. 9. Master model with Bilateral Control

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.

$$f = m\ddot{x} + d\dot{x} \tag{14}$$

Where,

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

$$k_t i^{ref} = f \tag{15}$$

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 figure 10, 11 depict the experimental setup of the forceps robot.

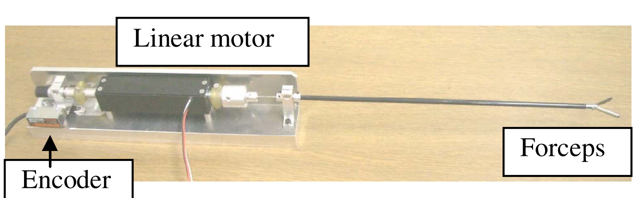

Fig. 10. Forceps connected to the Slave

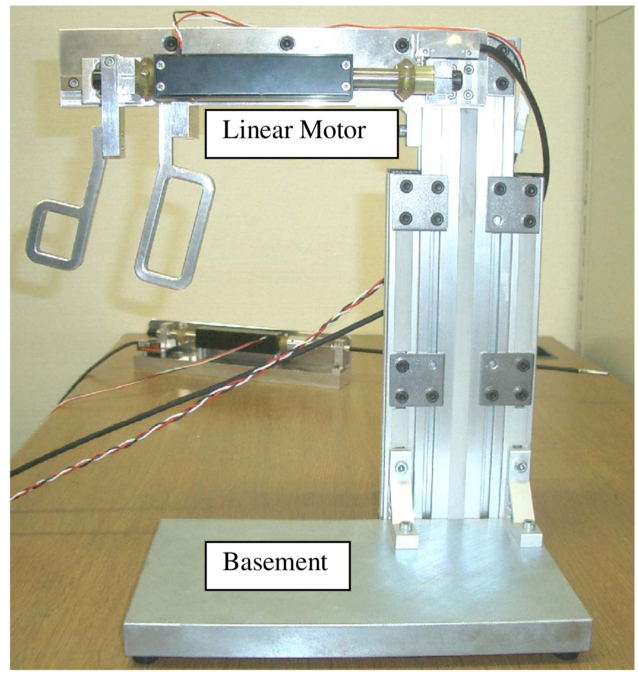

Fig. 11. Master Manipulator

V 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, soft jelly like material is kept for measurements. Initially, readings were taken without the virtual spring model. Then experiment is carried out with the virtual spring model at the slave side. Same rubber balloon is sensed through the embedded virtual master 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

V EXPERIMENT RESULTS

Virtual spring model is inserted. Response is measured without a slave load. Fig. 12 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 manipulators moved virtual model could be sensed at the gripper.

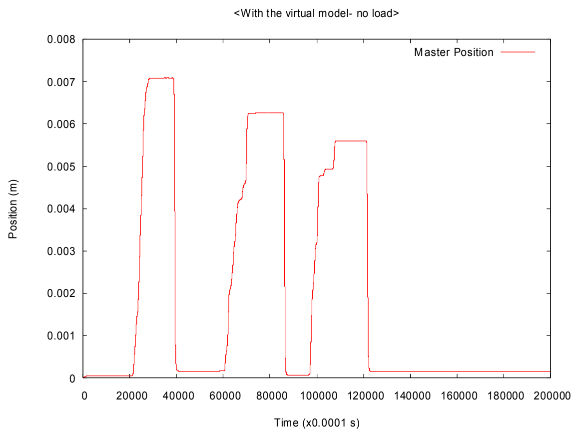

Fig.12a Master Position Response

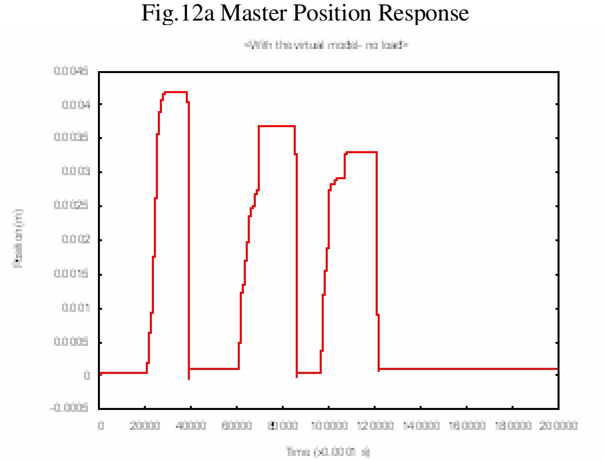

Fig.12b Slave Position Response

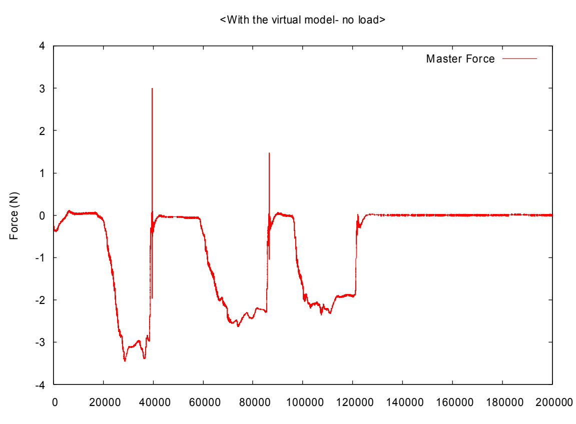

Fig.12c Master Force Response

As for the results, master and slave position responses have some differences. This is due to the virtual spring model which is exerted to the system. Force responses also have differences. This is due to the virtual model acting at the slave side. Spring damper model could be sensed through the master manipulator.

Fig. 12d. represents the slave force response. Two instantaneous peaks could be identified in the following figure. This is due to the sudden jerk of stopping at the position limit.

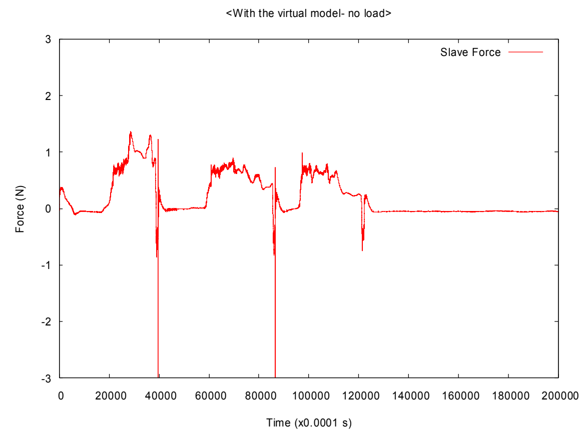

Fig.12d Slave Force Response

Finally, jell material is kept at the slave forceps when the virtual spring model is in action. Master manipulator is pressed once and released. These results are shown in the fig.13. Master and slave have returned to their original position indicating the virtual spring properties. Master force response is little bigger than the slave response. That is due to the virtual spring acting in the master side. Operator at the master side could feel the virtual tool reaction force together with the environment reaction.

Fig 13e depicts the force position response of the master manipulator. Gradient of the force position curve represents the stiffness. However, as for this experiment, force position curve represents the environmental stiffness as well as the virtual spring stiffness together. It shows some nonlinear characteristics which is due to the environment.

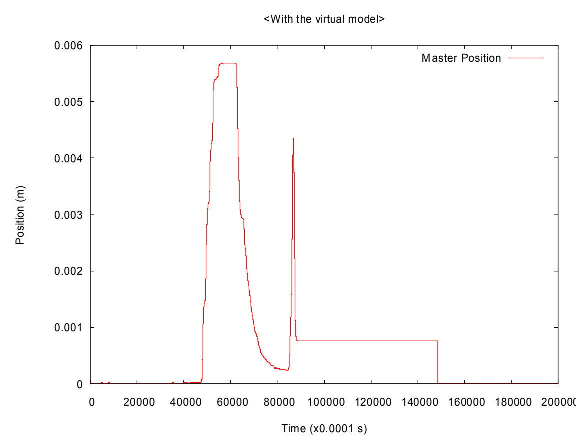

Fig.13a Master Position Response with load

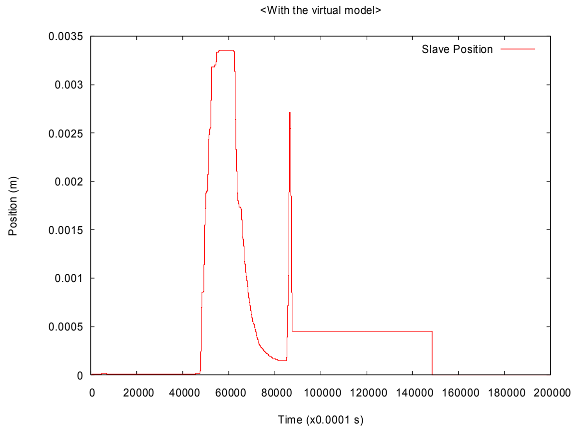

Fig.13b Slave Position Response with load

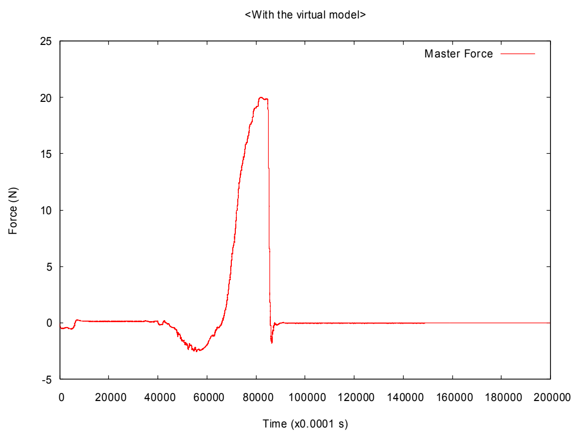

Fig.13c Master Force Response with load

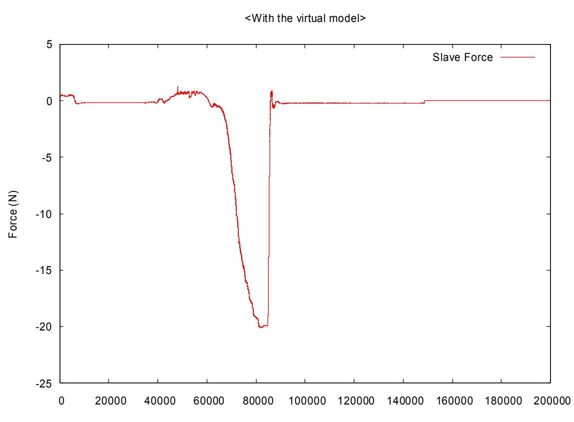

Fig.13d Master Force Response with load

VI CONCLUSION

In this paper, Virtual slave 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. Experiment was carried out to validate the proposal.

Virtual model adds a load to the system. Master and slave responses are slightly different. However, result is good enough for the application. Master operator could feel the vivid sensation coming through the slave side. Virtual model parameters were set such that they are large enough to perform virtual model action and small enough not to distort the feeling what is felt from the environment.

This novel approach could be used in many master slave applications. This method could be applicable in applications where the sensation what the master operator fees, should be different from the slave feeling or the slave action.

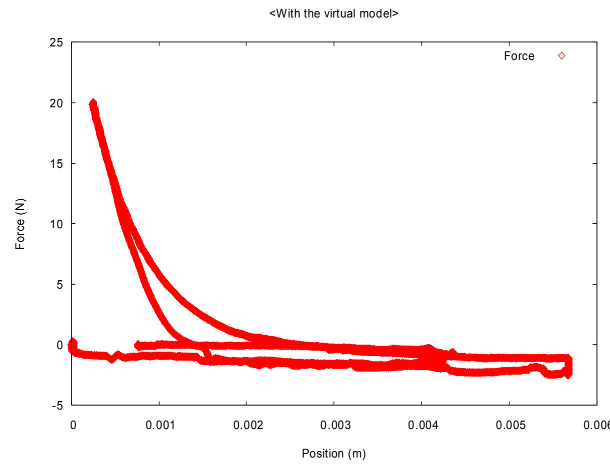

Fig.13e Master Force Position Response with load

VII. REFERENCES

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