Tactile Sensation Improvement of a Bilateral Forceps Robot with a Switching Virtual Model

A. M. Harsha S. Abeykoon* and Kouhei Ohnishi*
* Department of System Design Engineering,
Keio University,
3-14-1, Hiyoshi, Kouhoku, Yokohama,
Japan

***Abstract*—Interest of tele-operation started many decades ago. In day today lives tele-operation is getting a reality with improved tele-communication systems. Bilateral Control is also a subset of tele-operation. Usually in bilateral control, force position information is exchanged between master and slave. This structure successfully transmits tactile sensation from the slave environment to the master operator. Good bilateral system is capable of transmitting tactile sensation to the master side. This capability is also known as the transparency of a system. If bilateral control is used in a surgery, ideally the doctor should feel the feeling coming from the body tissue together with the reaction force of the special surgical tool. We proposed [6], [7] a method to eliminate the special surgical tool with a simple tool tip and a virtual tool model. However, physical tool as well as the proposed virtual tool, add impedance to the system. Even if virtual model is used, impedances are essential to carry out the tool action. In this paper a novel method is proposed to switch off and on the virtual tool model when the tool action can be replaced by the environmental reaction forces. Experiment was carried out using a bilaterally controlled forceps robot. Results show the applicability of the idea.**

I. INTRODUCTION

Teleoperation literally means operating a machine at a distance. Research on tele-operation has contributed to many technical advancements. Applications of Tele-operation systems can be classified in to three keywords. They are distance, accessibility and scale transfer. The keyword distance refers to the applications where tele-operation is used to combat the distance. Simple example would be a remote controller of a television. Second keyword refers to the accessibility to the environment that the machine operates. Teleoperation is extensively used in many hazardous environments where human operators are inaccessible. Tele-operation systems used in mines, outer space experiments etc. are examples for this. Scale transfer refers if the operator intends to operate a machine with a scale change from the input to the output. Macro micro manipulations, power assist systems, impedance scaling, power scaling and position scaling are examples for this. Tele-operation usually involves some kind of a feedback from the working environment. This may be a simple visual feedback or it can be sensed through the sensors kept at the work site.

A. Unilateral Control

Many controllers that we come across in day today lives are unilateral controllers. As the name implies, communication is done unilaterally. That is from the controller to the actuator. Tactile sensation cannot be transferred from the actuator with the unilateral control.

B. Bilateral Control

As the word ”bilateral” literally means, master and slave sides are controlled bilaterally. Slave side is controlled through the position and force information from the master side and the master side is controlled by the position and force information from the slave side. Therefore, this system enables the slave side environment to be reflected in the master side and master side operating intention reflected in the slave side. This concept is elaborated in section 2.

C. 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 advantages as the surgeon has to watch the monitor while doing the surgery. Master slave systems ”Da Vinci and Zeus” are examples for MIS robots. Main advantages of MIS include less healing time, less risks of infections and minimum blood loss. Rosen J. et al.[9] explain the necessity of the MIS. They provided a good explanation of why the doctor at a distance should be a reality in the future.

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. [2] 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 surgical environment and the tool impedance itself.

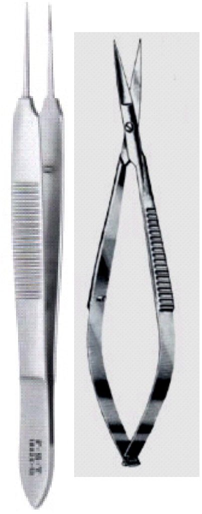

Fig. 1. Surgical tools - Spring action embedded as for the construction.

Skilled operators are very sensitive to the tools that they are used to. Surgeons are used to feel the tool reaction force as well as the feeling coming from the surgical environment. Fig.1 depicts such specialized surgical tools. A function of a spring is embedded in the construction.

D. Virtual tool

Many surgical tools are used during a surgery. However, lots of surgical tools carry similarities. Usually there is a similarity in the tool tip end. Consider the following expressions.

Simple tool tip + Virtual tool 1 = Complex tool 1

Simple tool tip + Virtual tool 2 = Complex tool 2

Suppose, simple tool and complex tool 1 and 2 carry similar tool tip ends. With the simple tool, various configurations such as complex tool 1 and 2 can be made with various virtual tools. In other words, tool change from complex tool 1 and 2 can be made with the simple change of the virtual tool. System downtime due to the tool change can be minimized with this method. In other words, when the end tool is similar, one end tool can be used in MIS. On the master side, various tool sensations can be recreated by having different virtual tool models. Fig.2 depicts the above idea. In a surgery special suture tying forceps can be replaced with a simple slave tool tip with a virtual tool. This idea was proposed by us [6],[7]. However, virtual model used was 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. This leads to a response error. Error tends to be dominant with smaller loads. In [11] we adopted a novel method so that there will not be any response error. 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 [11] were almost the same and it was a significant improvement.

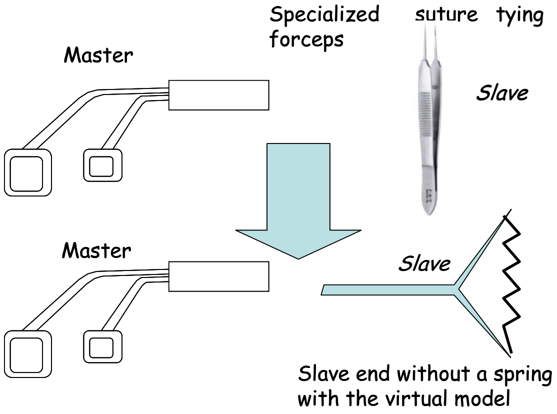

Fig. 2. Proposed virtual tool - example

Transparency [8] of a bilateral control is defined how well the system reproduces the slave environment at the master side. However in this paper we propose to alter the feeling which is coming from the slave side.
In the context of MIS,

Surgeon feels = Reaction force from the surgical environment + Operating tool reaction

Advantages of MIS could be summarized as follows.

- Frequent tool changes could be eliminated.
- Expensive and sophisticated tools can be replaced with simple tools.
- Downtime of tool change can be reduced.

The virtual model adds a load to the system. Though this load represents the tool properties, it distorts the feeling that is coming from the slave environment. On the other hand, virtual model is needed to accomplish the action of the tool. In this paper, it is proposed to switch the virtual model to the system only when its action is needed. For this paper virtual model represents a spring. Virtual spring is only needed when the reaction force from the environment is comparatively less. When environmental reaction is higher than the virtual model force, action of the virtual spring is not needed. It only adds impedance to the system which will distorts the real environment what is felt. This novel method will be tested for validity.

II. BILATERAL CONTROL

In this section bilateral control is introduced. Fig.3 shows the basic structure. 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 at 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 F_h force at the master side, and the manipulator moves by X_h, then the impedance of the master side is

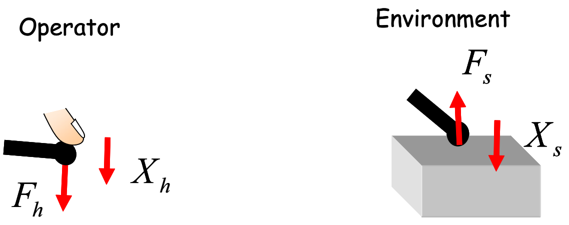

Fig. 3. Bilateral Control

Z_m. This can be shown by the equation (1).

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

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.

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

$$F_\mathrm{h} + F_s = 0 \tag{4}$$

However, in applications where master and slave are different, position and force scaling may be used. Fig.3 depicts the basic idea of bilateral control. Function of the disturbance observer and the reaction force observer will be discussed later in this text.

III. 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.

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

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

$$k_t i^{ref} = f \tag{6}$$

Where k_t is the force constant of the linear motor. Specifications of the linear motor Assembly are shown in Table 1.

TABLE I
SPECIFICATIONS OF LINEAR MOTOR ASSEMBLY

Maximum force	30N
Current	0.5A
Resolution	1μm
Thrust Constant	20N/A
Stroke Length	4mm
Movable Weight	100g
Physical Weight	340g

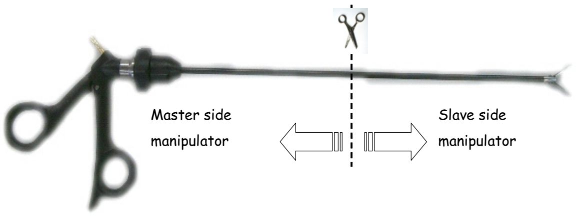

Fig. 4. Slave and Master manipulators are made by cutting the forceps

B. Forceps Robot

Forceps robot is used for this experiment. Following Figure shows forceps that is used in surgeries. Conceptually, slave and master manipulators are made by cutting the forceps as depicted in Fig.4. Fig.5 depict the robotic manipulators used for this experiment. This robot has only one degree of freedom. For a practical surgery, the robot has to work in multi degrees of freedom. However, this robot is sufficient enough to demonstrate this novel method and its applicability.

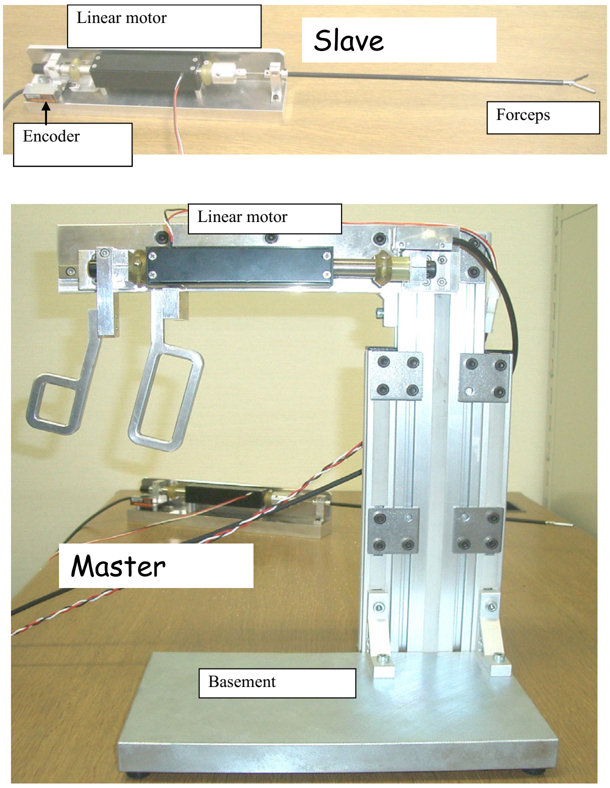

Fig. 5. Experimental Setup

IV. MODELLING

Manipulators do not have any physical springs in the construction. During a surgery, if the tool has to be changed to a tool with a spring at the tool tip end, a virtual spring can work in place of the actual spring. Fig.6 shows the virtual model inserted in-between the forceps grippers.

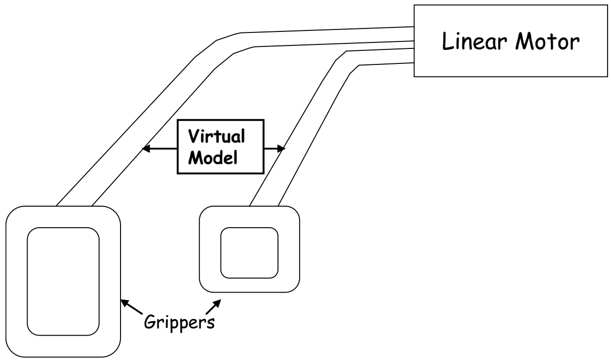

Fig. 6. Master manipulator with the Virtual Model

Therefore, master operator should feel the spring as well as the reaction force from the environment. Spring is modelled with a spring damper model depicted in Fig.7.

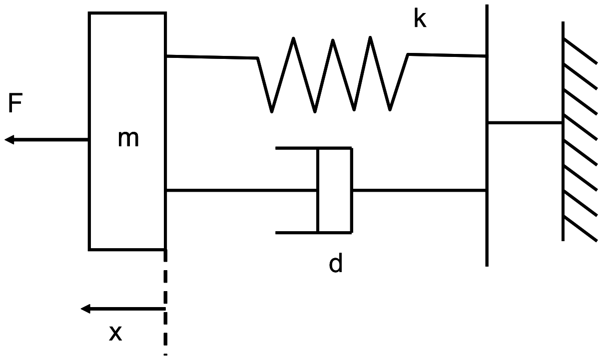

Fig. 7. Virtual Spring Damper Model

Dynamic equation of the spring damper model is,

$$F = m\ddot{x} + d\dot{x} + kx \tag{7}$$

Where,
m: Normal Mass
d: Damping Coefficient
k: Spring Constant

In Laplace Domain,

$$F(s) = \left[ms^2 + ds + k\right] X(s) \tag{8}$$

However, for this experiment simple spring model was used instead of the spring damper model. Upper part of Fig.8 shows the full control system. Lower part shows the expansion of the "decision Logic" block.

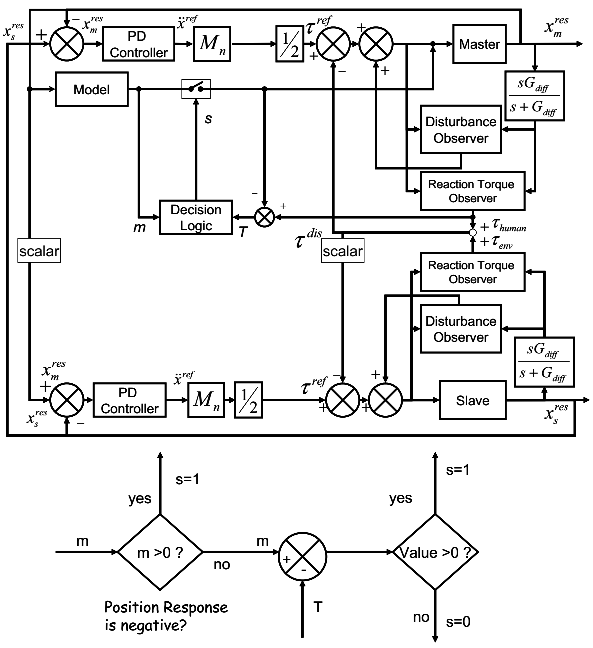

Fig. 8. Total Control System

Master and slave side manipulators are controlled with two identical PD controllers. As for this experiment, masses of the Master side linear motor (M_n) and Slave side are equal. Position outputs of the master and slave are exchanged as inputs to the slave and master respectively. $DisturbanceObserver$ is used to cancel out the disturbances and to have robust motion control. It's variant, $ReactionForceObserver$ is used as the force sensor. There are no physical force sensors used in this experiment. Reaction force observer and disturbance observer are explained in detail in the next section. Position and force scaling factors are set to 1, so that virtually there is no scaling involved.

Switching will be done according to the Decision logic. m, model input carries the sign of the moving direction. If m is positive it means position response is in the reverse direction. Then s is assigned 1, representing model is switched on to the system. Reaction force observer's output carry a component of the virtual model. T is calculated by eliminating the virtual model component from the reaction force output. Next decision point depends whether the force from the virtual model is greater than the T coming from the master side. When m, the model output is greater than the resultant force T, reaction force is weak and not enough. Then switch is kept ON and virtual model is continued to be used for the model action. When the T is larger, reaction force is big enough to compliment the virtual model's action. Then virtual model is switched OFF.

V. DISTURBANCE OBSERVER AND REACTION FORCE OBSERVER

This section initially explains the basics of the disturbance observer and its variant reaction force observer. Then the discussion is extended to explain how these observers are used in this research.

Dynamic equation of a linear motor is expressed by (9).

$$M\ddot{x} = F_g - F_l \tag{9}$$

Where,
M: Nominal Mass
x: Linear Distance
F_g: Generated force
F_l: Load

Generated force F_g,

$$F_g = K_t I_a = K_t I_a^{ref} \tag{10}$$

k_t is the force coefficient. It is a function of flux position of the linear motor. I_a is the load current. With a fast switching power supply it is possible to approximate the load current I_a as the force current reference I_a^{ref}.

Load force F_l can be represented as (11).

$$F_l = F_{\text{int}} + F_{ext} + (F + D\dot{x}) \tag{11}$$

Where,
F_{int}: Interactive torque including cariolis and gravity terms
F_{ext}: Reaction force of the mechanic load
F : Coulomb friction
$D\dot{x}$: Viscous friction

By subtracting (10) by (11), (9) can be re-written as (12).

$$M\ddot{x} = K_t I_a^{ref} - (F_{\text{int}} + F_{ext} + F + D\ddot{x}) \tag{12}$$

Parameters of a system are subjected to variations and estimation errors. Parameters of (12) k_t and M can be re-written in terms of nominal values and variations.

$$M = M_n + \Delta M \tag{13}$$

$$K_t = K_{tn} + \Delta K_t \tag{14}$$

The total disturbance to the system F_{dis} is represented as,

$$\begin{aligned} F_{dis} &= F_l + \Delta M\ddot{x} - \Delta K_t I_a^{ref} \\ &= F_{\text{int}} + F_{ext} + F + D\dot{x} + \\ &\quad (M - M_n)\ddot{x} + (K_{tn} - K_t) I_a^{ref} \end{aligned} \tag{15}$$

Disturbance Observer is shown in Fig.9 Disturbance is calculated from I_a^{ref} and $\dot{x}^{res}$ Disturbance is fed to a first order low-pass filter to calculate the estimated disturbance force. Estimated disturbance $\hat{F}_{dis}$ is given by (16).

$$\hat{F}_{dis} = \frac{g_{dis}}{s + g_{dis}} F_{dis} \tag{16}$$

Cut off frequency of the low-pass filter is represented as g_{dis} Robust control system is attained by using the disturbance observer. This system can be represented as an acceleration control system [1]. Force between the human operator and the environment can be represented as (17).

$$\begin{aligned} F_{hum} = F_e &= M_e\ddot{x} + D_e\dot{x} + k_e x \\ &= \left(M_e s^2 + D_e s + k_e\right) x \\ &= Z_e x \end{aligned} \tag{17}$$

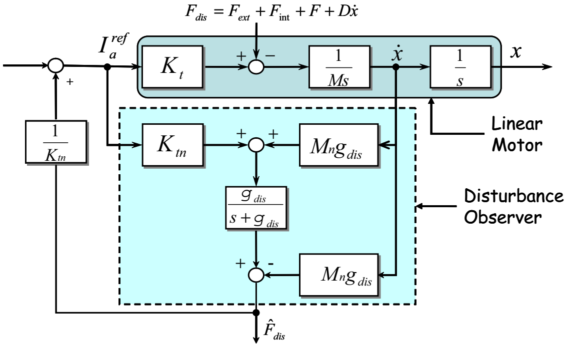

Fig. 9. Disturbance Observer with linear motor

Where,
M_e : Environmental Mass
D_e : Environmental Damping
k_e : Environmental Impedance

Identification of the disturbance force is not only effective for realization of robust motion control but also to identify parameters as well. This enables to identify the friction effects[1] of the system. External forces also could be identified using disturbance observer [4]. Therefore, if frictional elements are known beforehand and parameters could be adjusted so that they are very close to the actual values. After the identification process, disturbance observer acts as a reaction force observer. Usually for practical applications, disturbance observer and reaction force observer could be identical, provided the cut off frequencies are equal.

Output of the virtual model is acting equivalently to an external force. Thus the output is estimated by the observers as a force. Disturbance observer uses this output for robust motion control. The force output of the reaction force observer is exchanged equivalently between the master and slave.

VI. EXPERIMENT AND RESULTS

The forceps robot depicted in Fig.5 was used for the experiment. Human operator directly manipulates the master system. At the end of the forceps, spongy material is kept for measurements. Same spongy material is sensed through the embedded virtual model with switching. Following parameters were used for the experiment.

Following parameters were used for the experiment.

TABLE II
EXPERIMENTAL PARAMETERS

k_p	Position Gain	9000m/s
k_v	Velocity Gain	200m/s
k_{tn}	Force Coefficient	20N/A
k	Spring Constant	1000N/m
St	Sampling Time	0.0001s

Fig.11 depicts the results when virtual model is in action with the bilateral control. The force is sensed through the master manipulator. Slave forceps end is kept open (normally open). Master manipulator was moved, so that the spongy material kept at the slave end is squeezed. This was repeated three times.

During the free movement, spring action could be sensed. Switching has reduced the impedance when the material is squeezed.Position responses are almost the same. Fig.10 shows the perfectly matched position responses of master and slave.

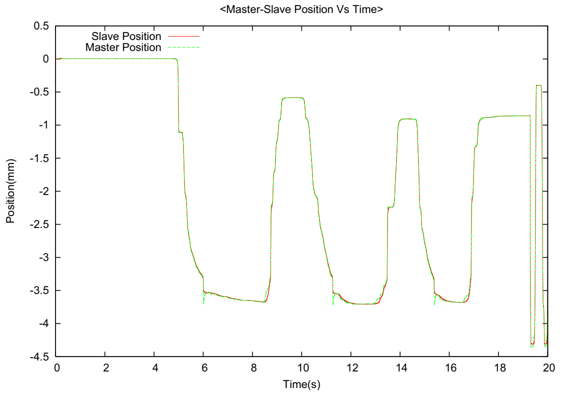

Fig. 10. Master-Slave position responses together

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.11 shows a perfect match of force responses as well. Vivid sensation could be transferred from the slave side to the master side.

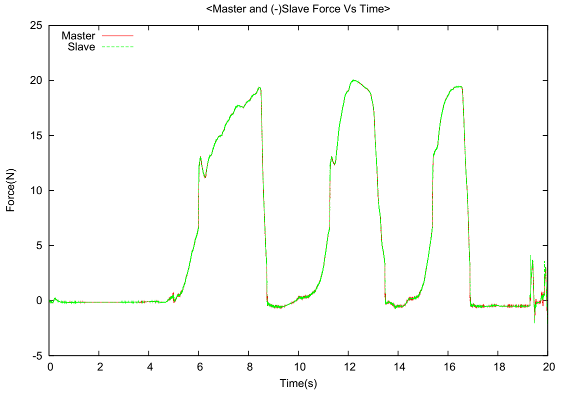

Fig. 11. Master-Slave Force Responses together

Fig.12 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. Slope represents the virtual model.

Green line represents the variations without switching. Red variation corresponds to the ”with switching” scenario. Both variations carry similarities of the lines parallel to the X axis. Green curve has a smooth turning point and red curve has a sharp turning point. Difference should be due to the variations of the switching.

VII. CONCLUSION

In this paper, a Virtual model was proposed; specially for Minimally Invasive Surgeries. By changing the model,

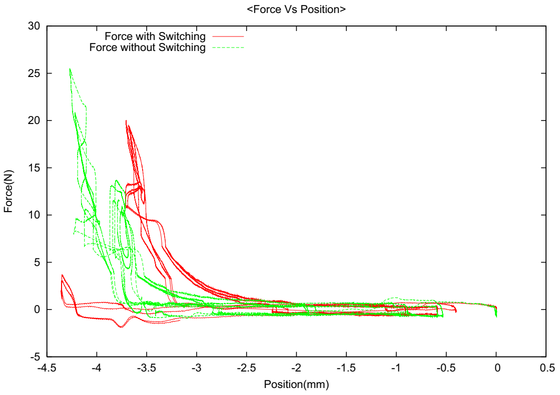

Fig. 12. Force-Position responses with and without switching

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 and loads together with the virtual model. Virtual model was switched to the system when it is needed. 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.

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