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Reaction Force Estimation of Surgical Robot Instrument Using Perturbation Observer with SMCSPO Algorithm

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Abstract— **This paper proposes a sensorless force estimation method for the end effector tip of a surgical robot instrument. Due to various size and safety constraints related to the surgical robot instrument, it is difficult to measure the reaction force at the instrument tip. This paper presents a method of estimating the reaction force of the surgical robot instrument without sensors and attempts to use state observer of control algorithm. Sliding mode control with sliding perturbation observer (SMCSPO) is used to drive the instrument, where the sliding perturbation observer (SPO) computes the amount of perturbation defined as the combination of the uncertainties and nonlinear terms where the major uncertainties arise from the reaction force. Based on this idea, this paper proposes a method to estimate the reaction force on the end-effector tip of the surgical robot instruments using only SPO and encoder without any additional sensors. To evaluate the validity of this paper, experiment was performed and the results showed that the estimated force computed from SPO is similar to the actual force.**

I. INTRODUCTION

MINIMALLY invasive surgery (MIS) and laparoscopy assisted surgery (LAS) have been substituted alternatively for traditional open surgery, since they minimize the pain of recovery and the period of hospitalization is shortened by eliminating the large incision and extensive dissection. With advancement in robot technologies, surgical robot for MIS has been developed and has produced good results leading to fast recovery with low pain and lower infection rate than general open invasive surgery [1]. During surgical robot operates MIS, instead of surgeon’s hands, the robot instrument conducts the operation with high DOF and multi function ability. The motion of instrument traces the surgeon’s hand motion at the console located far from patients. Fig. 1 shows the one such commercial surgical instrument, EndoWrist [2]. For efficient operation the surgical instruments must follow surgeon’s dexterous skillful motion. This also requires that the surgeon should be able to feel the real tactile sensation in the body and control delicately the strength of grasping, similar to the open invasive surgeries. Therefore, haptic sense feedback needs to be provided so that the surgeon can feel the sensation in order to do the force control. However, operating instruments inside a body prohibit attaching electronic sensors in addition to space restrictions in MIS. Thus, all instruments of surgical robot are driven simply in position control. As a result, some medical papers have reported that doctors who used the commercialized surgical robot faced some problems in procedures like pulling and tying thread, suturing tissue, and cutting tissues due to difficulty in force control [3].

Due to the constraints related to the surgical robot instruments, the forces should be measured indirectly. There are several methods to estimate or measure the force indirectly. One way to estimate force was suggested by measuring the current flowing across the driving motor [4].

However it is difficult to distinguish between reaction force and dynamic force according to robot motion. Cable-pulley based mechanical structure system was also proposed to analyze friction force and to measure the reaction force by using a load cell [5]. The overcoat method to measure the contact force loaded on the tip of the surgical robot was proposed [6]. The effects of substituting direct haptic feedback with visual and auditory cues was studied [7].

Fig. 1. Instrument and tip for Davinci Surgical Robot [2]

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For sensing instrument reaction force, a method to overcome the physical limitations of instrument is suggested [8]. However, those methods also have a problem to use a force sensor or attach the sensor on the instrument tip, or visual feedback. As opposed to those methods which need additional sensors, this paper presents a method which does not require additional sensors or changing the mechanical design, by using the state observer which estimates the reaction forces in surgical robot instrument. This paper proposes the method to estimate the reaction force to supply feedback cue for haptic system, which allows force controlled robot surgery.

Most of commercial surgical robot instruments adopt cable-pulley mechanism, similar to human tendons because of the size and safety. However, cable-pulley mechanism is highly nonlinear system due to the tension losses in the cable and its complex structure [9]. This paper attempts to use sliding mode control with sliding perturbation observer (SMCSPO) as a robust control algorithm to overcome nonlinearity and disturbance. Sliding observer (SO) is a high performance state estimator well suited for nonlinear uncertain systems with partial state feedback [10],[11]. There is additional observer in SMCSPO, which is sliding perturbation observer (SPO) [12]. In this paper, the perturbation implies not only the modeling error and nonlinear terms but also external force applied to motor. It is assumed that the nonlinearities in the surgical instrument is small compared to the reaction forces in procedure like cutting thread, breaking needle, and harming organs. Thus, the estimated perturbation would be close to the external force.

This paper utilizes the estimated value of uncertainty in SPO. Applied to surgical robot instrument, SPO may estimate the reaction force on the surgical instrument tip as using only the state equation and state values, which does not require any sensors except the motion encoder attached on the motor.

The next section explains SMCSPO in details. In the third section, experimental test results are presented to examine the validity of the proposed idea, followed by concluding notes in the last section.

II. Sliding Mode Control with Sliding Perturbation Observer

A. Definition of Perturbation

This section defines the perturbation which includes uncertainty due to the reaction force against the system. Using the SPO, the assumed perturbation could be estimated as the reaction force of the surgical robot instrument[12][13][15]. Generally, the governing equation of a class of nonlinear system is defined as

$$\mathbf{x}^{(n)} = \mathbf{f}(\mathbf{X}_1,\cdots,\mathbf{X}_m) + \Delta\mathbf{f}(\mathbf{X}_1,\cdots,\mathbf{X}_m) + \left[\mathbf{B}(\mathbf{X}_1,\cdots,\mathbf{X}_m) + \Delta\mathbf{B}(\mathbf{X}_1,\cdots,\mathbf{X}_m)\right]\mathbf{u} + \mathbf{d}(t) \quad (1)$$

where

$\mathbf{x} \equiv [\mathbf{X}_1, \mathbf{X}_2, \cdots, \mathbf{X}_m]^T \in \mathbb{R}^m$: the global state vector

$\mathbf{X}_i \equiv [x_i, \dot{x}_i, \cdots, x_i^{(n_i-1)}]^T \in \mathbb{R}^{n_i}$, $i = 1,\cdots,m$: the i-th state sub-vector, which forms the global state vector

$\mathbf{f} = [f_1, \cdots f_m]^T \in \mathbb{R}^m$ and $\Delta\mathbf{f} = [\Delta f_1, \cdots \Delta f_m]^T \in \mathbb{R}^m$: vector corresponding to the nonlinear driving terms and their uncertainties, respectively

$\mathbf{B} = [b_{ij}] \in \mathbb{R}^{m\times m}$ and $\Delta\mathbf{B} = [\Delta b_{ij}] \in \mathbb{R}^{m\times m}$, $i, j = 1,\cdots,m$: matrices representing control gains and their uncertainties

$\mathbf{d} = [d_1, \cdots d_m]^T \in \mathbb{R}^m$: disturbance vector of the system

$\mathbf{u} = [u_1, \cdots u_m]^T \in \mathbb{R}^m$: control vector

$\mathbf{x}^{(n)} = [\mathbf{X}_1^{(n_1)}, \cdots \mathbf{X}_m^{(n_m)}]^T \in \mathbb{R}^m$, $\mathbf{X}_i^{(n_i)} \in \mathbb{R}$ with

$$x_i^{(k)} = \frac{d^k(x_i)}{dt^k},\ \dot{x}_i = \frac{d(x_i)}{dt}$$

The uncertainties $\Delta\mathbf{f}$, $\Delta\mathbf{B}$, and external disturbance $\mathbf{d}$ are unknown but assumed to be bounded by a known continuous functions of $\mathbf{X}_i$ [11].

In the governing equation, perturbation is defined as the combination of all the uncertainties and external disturbance of Eq. (1).

$$\mathbf{\Psi}(\mathbf{X}_1,\cdots,\mathbf{X}_m,t) = \Delta\mathbf{f}(\mathbf{X}_1,\cdots,\mathbf{X}_m) + \Delta\mathbf{B}(\mathbf{X}_1,\cdots,\mathbf{X}_m)\mathbf{u} + \mathbf{d}(t) \quad (2)$$

The control task is to derive the state sub-vector toward a desired state vector $\mathbf{X}_{id} \equiv [x_{id}, \dot{x}_{id}, \cdots, x_{id}^{(n_i-1)}]^T$ despite these perturbations [11]. It is assumed that the perturbations are upper bounded by a known continuous function of the state such as

$$\Gamma(\mathbf{X}_1,\cdots,\mathbf{X}_m,t) = F(\mathbf{X}_1,\cdots,\mathbf{X}_m) + \left|\Phi_{ji}(\mathbf{X}_1,\cdots,\mathbf{X}_m)\mathbf{u}\right| + D(t) > \left|\mathbf{\Psi}(t)\right| \quad (3)$$

where $F > |\Delta\mathbf{f}|$, $\Phi > |\Delta\mathbf{B}|$, and $D > |\mathbf{d}|$ represent the expected upper bounds of the uncertainties, respectively.

B. Sliding Perturbation Observer

The new control variable that is used in order to decouple the control of Eq. (1) is defined as

$$\mathbf{f}(\hat{\mathbf{X}}_1,\cdots,\hat{\mathbf{X}}_m) + \mathbf{B}(\hat{\mathbf{X}}_1,\cdots,\hat{\mathbf{X}}_m))\mathbf{u} = \alpha_{3j}\bar{u}_j \quad (4)$$

where x is the state, α_{3j} is an arbitrary positive number and $\bar{u}_j$ is the new control variable [12],[13]. Throughout the text, "~" and "^" symbolize the estimation errors and estimated quantity, respectively.

The state representation of the simplified dynamics of the instrument is defined as

$$\dot{x}_{1j} = x_{2j} \quad (5a)$$

$$\dot{x}_{2j} = \alpha_{3j}\bar{u}_j + \Psi_j \quad (5b)$$

$$y_j = x_{1j} \quad (5c)$$

where j is the number of robot arm joint.

Let x_{3j} related to the perturbation be a new state variable defined as

$$x_{3j} = \alpha_{3j} x_{2j} - \Psi_j / \alpha_{3j} \tag{6 a}$$

$$\dot{x}_{3j} = \alpha_{3j} \dot{x}_{2j} - \dot{\Psi}_j / \alpha_{3j} \tag{6 b}$$

If the gain α_{3j} is selected as high enough value, the variable $\dot{\Psi}_j / \alpha_{3j}$ can be neglected. It means that the estimated state x_{3j} can reduce influence by the perturbation term. In order to accomplish this, it is assumed that the perturbations are continuous and lie within a known finite frequency range [14],[15].

The estimated perturbation $\hat{\Psi}_j$ needs the estimated state, x_{2j}. The sliding perturbation observer is better than the general one because this observer can provide an on-line perturbation estimation scheme using only partial state feedback. Also, the estimation accuracy of x_{2j} improves the accuracy of the perturbation estimation. This structure can be achieved by writing the observer equation from Eqs. (5a), (5b), (6a), and (6b) as

$$\dot{\hat{x}}_{1j} = \hat{x}_{2j} - k_{1j} sat(\tilde{x}_{1j}) - \alpha_{1j} \tilde{x}_{1j} \tag{7a}$$

$$\dot{\hat{x}}_{2j} = \alpha_{3j} \bar{u}_j - k_{2j} sat(\tilde{x}_{1j}) - \alpha_{2j} \tilde{x}_{1j} + \hat{\Psi}_j \tag{7b}$$

$$\dot{\hat{x}}_{3j} = \alpha_{3j}^2 (-\hat{x}_{3j} + \alpha_{3j} \hat{x}_{2j} + \bar{u}_j) \tag{7c}$$

where $\hat{\Psi}_j$ is derived as

$$\hat{\Psi}_j = \alpha_{3j} (-\hat{x}_{3j} + \alpha_{3j} \hat{x}_{2j}) \tag{8}$$

as $k_{1j},\ k_{2j},\ \alpha_{1j},\ \alpha_{2j} > 0$

$\tilde{x}_{1j} = \hat{x}_{1j} - x_{1j}$ is the estimation error of the measurable state, and $sat(\tilde{x}_{1j})$ is the saturation function for the existence of sliding mode[10], [11].

C. SMCSPO Design

Basically, this paper studies how to measure the reaction force without sensors and attempt to estimate it by using SPO. Thus, the instrument should be controlled based on SMCSPO. This section explains the method of SMCSPO design. Fig. 2 shows the block diagram of SMCSPO.

As a general sliding mode control, the estimated sliding function is defined as

$$\hat{s}_j = \dot{\hat{e}}_j + c_{j1} \hat{e}_j \tag{9}$$

where $c_{j1}(>0)$ is a slope of switching line and $\hat{e}_j (= \hat{x}_{1j} - x_{1dj})$ is the estimated position tracking error. $[x_{1dj}\ \dot{x}_{1dj}]^T$ are the desired states for the motion of the robot

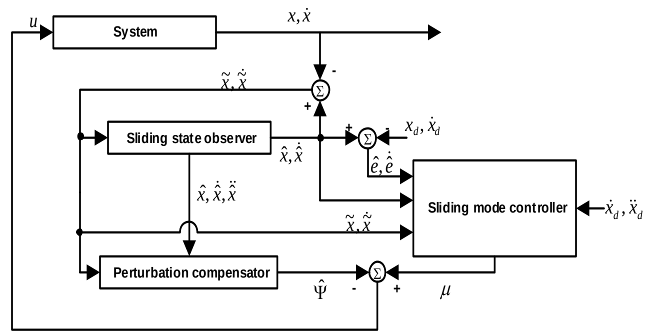

Fig. 2. Block diagram of SMCSPO

arm. The control $\bar{u}_j$ is selected to satisfy $\dot{\hat{s}}_j^T \hat{s}_j < 0$ outside a prescribed manifold. A desired $\dot{\hat{s}}_j$ is like as

$$\dot{\hat{s}}_j = -K_j sat(\hat{s}_j) \tag{10}$$

where

$$sat(\hat{s}_j) = \begin{cases} \hat{s}_j / |\hat{s}_j|, & if\ |\hat{s}_j| \geq \varepsilon_{sj} \\ \hat{s}_j / \varepsilon_{sj}, & if\ |\hat{s}_j| \leq \varepsilon_{sj} \end{cases} \tag{11}$$

Eq.(11) is used to reduce the chattering problem and $K_j(>0)$ is the robust control gain. In this equation, ε_{sj} depicts the width of boundary layer of the SMC, which is different value with the boundary layer ε_{oj} in SPO [12].

Using Eqs. (7), (8), (9), (10), and (11), it is possible to compute $\dot{\hat{s}}_j$ as

$$\dot{\hat{s}}_j = \alpha_{3j} \bar{u}_j - [k_{2j}/\varepsilon_{oj} + c_{j1}(k_{1j}/\varepsilon_{oj}) - (k_{1j}/\varepsilon_{oj})^2] \tilde{x}_{1j} + \ddot{x}_{1dj} + c_{j1}(\hat{x}_{2j} - \dot{x}_{1dj}) + \beta_j \hat{\Psi}_j \tag{12}$$

The resulting $|\hat{s}_j|$-dynamics including the effects of $\tilde{x}_{2j}$ is selected as

$$\dot{\hat{s}}_j = -K_j\ sat(\hat{s}_j) - (k_{1j}/\varepsilon_{oj}) \tilde{x}_{2j} - K_{Sj} \hat{s}_j - K_{Rj} \sigma_j \tag{13}$$

where $\sigma_j = \sum_{k=1}^{n_j - 1} \eta_{j,k+1} e_j^{(k)}$, $\eta_{j,k+1} \in \mathbb{R}_+$, $\eta_{j,n_j} = 1$ and $K_{Sj}(>0)$ is the recursive filter gain. $K_{Rj}(>0)$ is the robust control gain to remove the restrictions of SMC and SPO. In order to enforce Eq. (13) when $\tilde{x}_{2j} = 0$, a control law from Eqs. (12) and (13) is selected as

$$\begin{aligned} \bar{u}_j = \frac{1}{\alpha_{3j}} \{ & -K_j sat(\hat{s}_j) - (k_{1j}/\varepsilon_{oj}) \tilde{x}_{2j} \\ & + [k_{2j}/\varepsilon_{oj} + c_{j1}(k_{1j}/\varepsilon_{oj}) - (k_{1j}/\varepsilon_{oj})^2] \tilde{x}_{1j} + \ddot{x}_{1dj} \\ & - c_{j1}(\hat{x}_{2j} - \dot{x}_{1dj}) - K_{Sj} \hat{s}_j - K_{Rj} \sigma_j - \beta_j \hat{\Psi}_j \} \end{aligned} \tag{14}$$

where β_j is positive gain of perturbation and $\beta_j \hat{\Psi}_j$ is upper bounded by a known continuous function of the state such as Eq. (3).

When SPO is combined with SMC strategy, the saturation functions to decrease the control chatter and to smooth the discontinuous sgn($\tilde{x}_{1j}$) are defined as

$$sat(\tilde{x}_{1j}) = \begin{cases} \tilde{x}_{1j} / \left| \tilde{x}_{1j} \right|, & if \quad \left| \tilde{x}_{1j} \right| \geq \varepsilon_{oj} \\ \tilde{x}_{1j} / \varepsilon_{oj}, & if \quad \left| \tilde{x}_{1j} \right| \leq \varepsilon_{oj} \end{cases} \tag{15}$$

The observer's sliding mode takes place on the line $\tilde{x}_{1j} = 0$ of the observer state space $\tilde{x}_{1j}$ vs. $\tilde{x}_{2j}$. The conditions for the existence of sliding mode are derived as

$$\tilde{x}_{2j} \leq \alpha_{1j}\, \tilde{x}_{1j} + k_{1j} \quad (if \quad \tilde{x}_{1j} > 0) \tag{16a}$$

$$\tilde{x}_{2j} \geq \alpha_{1j}\, \tilde{x}_{1j} - k_{1j} \quad (if \quad \tilde{x}_{1j} < 0) \tag{16b}$$

From the sliding condition in Eq. (16), the state estimation error is bounded by $\left| \tilde{x}_{2j} \right| \leq k_{1j}$. Therefore, in order to satisfy $\dot{\hat{s}}_j^{\,T} \hat{s}_j < 0$ outside the manifold $\left| \hat{s}_j \right| \leq \varepsilon_{oj}$, the robust control gains must be chosen such as

$$\begin{aligned} & K_j \geq (\Delta \mathbf{f} + \Delta \mathbf{Bu} + \mathbf{d})_{j,\, worst\ case} \\ & K_j \geq K_{Sj} \geq K_{Rj} \geq k_{1j} / \varepsilon_{oj} \end{aligned} \tag{17}$$

A systematic general design procedure considering the hardware limitations of the system is described by the fact that the eigenvalues of the characteristic equation of systematic matrix of observer and s_j dynamics are negative real number. For simplicity, all the desired poles are selected to be the same real value located at $\lambda = -\lambda_d (\lambda_d > 0)$. This leads to the following design solution.

$$\begin{aligned} & \frac{k_{1j}}{\varepsilon_{oj}} = 3\lambda_d \ , \quad \frac{k_{2j}}{k_{1j}} = \lambda_d \ , \\ & \alpha_{3j} = \sqrt{\frac{\lambda_d}{3}} \ , \quad c_{j1} = K_j / \varepsilon_{oj} = \lambda_d \end{aligned} \tag{18}$$

Physical limitations of the control system define the optimum placement of λ_d. The λ_d is effected by hardware constraints such as sampling frequency, dominant time delay, measurement delay, and actuator dynamics [12][13].

III. EXPERIMENTAL VERIFICATION

In the previous studies, it was shown that the cable pretension is important design factor in pull-pull structure power transmission like surgical robot instrument and can be related with frictional torque by analyzing the dynamics [9]. The force is transmitted by tension differential between the pair of cables making it a complex nonlinear system. The previous studies attempted to use SMCSPO as robust controller which can overcome the nonlinearities and frictional forces [15]. This paper focuses on perturbation during control routine, since perturbation implies not only modeling error but also torque applied on the motor. Measuring the perturbation including a reaction force of the surgical robot instrument is still difficult problem which needs to be addressed due to its importance. In Eq. (2), the perturbation is defined as the combination of system uncertainties, nonlinear term and disturbance which is the loaded force in the instrument. And in Eq. (8) this parameter can be calculated by using the state equation. Therefore, it is assumed that the perturbation value follows the reaction force of the instrument closely if other uncertainties except the external force are small enough compared to the reaction force. To ascertain this assumption, experimental test is carried out to find the relation between the operating load and perturbation value.

A. Experimental System

Experimental test used EndoWrist instrument which is used by Da Vinci surgical robot, the representative commercial surgical robot. The instrument test kit was built as shown in Fig. 3. The specification of test kit is listed in Table. I. Four motors were used to drive 4 links of the instrument. Fig. 4 explains the movement of instrument and rotation of motors. Fig. 5 shows experimental system to measure the reaction force on the instrument tip. Fig. 6 shows the master grip to open and close the jaws of the tip.

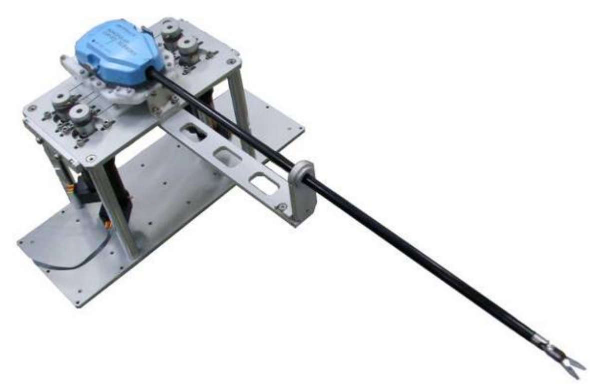

Fig. 3. Robotic instrument test kit

TABLE I SPECIFICATION OF EXPERIMENTAL TEST SYSTEM

Part	specification
Instrument	Intuitive EndoWrist Instrument (Maryland Bipolar Forceps)
Motor	4 pcs of Maxon DC Motor (Φ26mm, 18W graphite brushes)
Encoder	4pcs of Maxon Encoder (3 Channel Optical Encoder)
Motor drive	Maxon motor Control (Servo amplifier)
Controller	DSP(TMS320F28335)
Sample time	0.5 ms

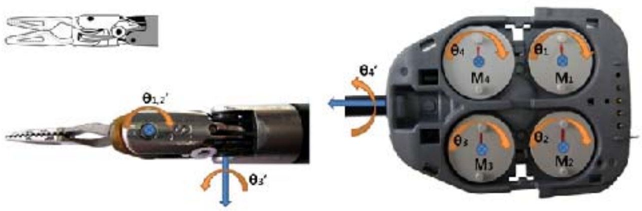

Fig. 4. Coordinate explanation of instrument tip and input dial

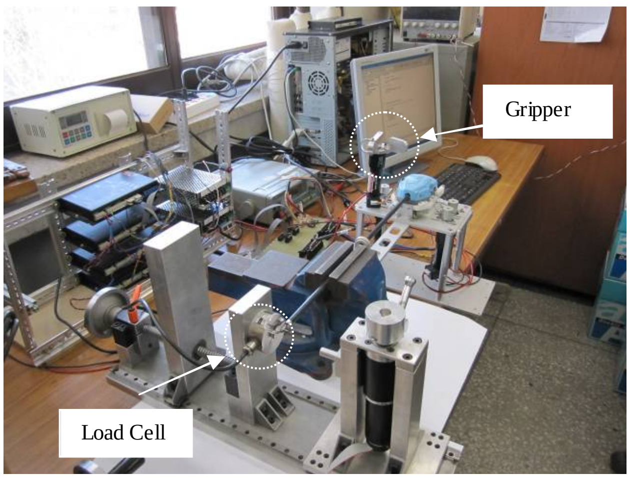

Fig. 5. Experimental system to measure reaction force by using load cell

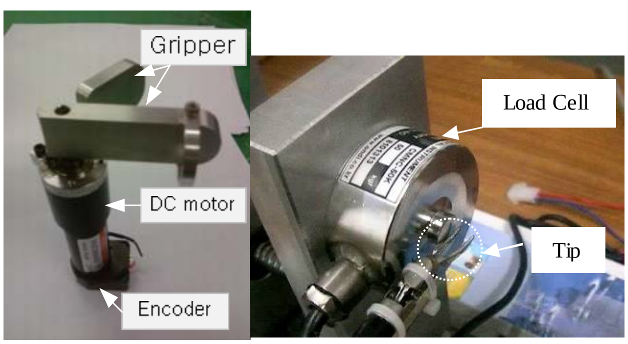

Fig. 6. Haptic functional master joystick and load cell to measure reaction force

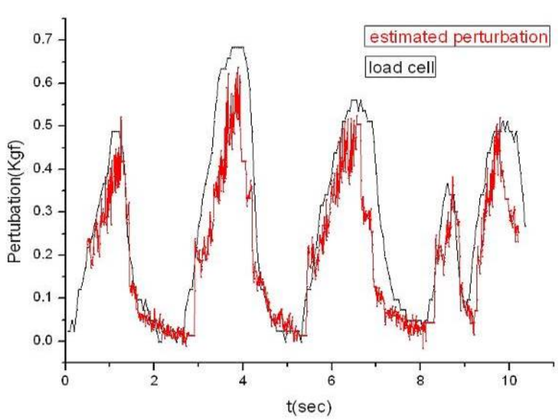

Fig. 7. Experimental result

TABLE II DESIGNED PARAMETERS OF SMCSPO

Parameter	Value
$\lambda_d = k_{2j}/k_{1j} = c_{j1}$	350 rad/s
$k_{1j} / \varepsilon_{oj}$	1050rad/s
α_{3j}	$\sqrt{350/3}$ rad/s

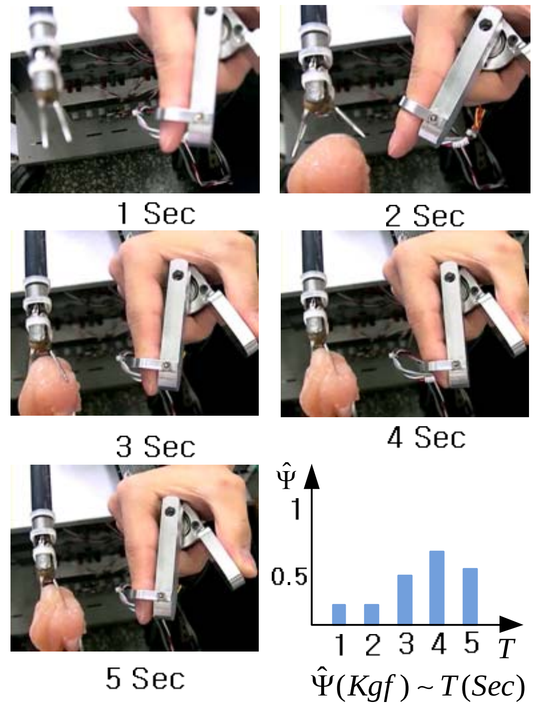

Fig. 8. Haptic functional Experiment

B. Perturbation Evaluation

To find the relationship between the reaction force and the estimated perturbation value, the force should be measured by experiment. To measure the reaction force, load cell was used with the test system as shown in Fig. 5. One instrument tip is driven towards the load cell where it touches the center of the load cell in zero position. The rest of the instrument body is kept fixed. The input signal is generated by master joystick as shown in Fig. 6. The designed parameters of SMCSPO in Eq. (18) are listed in Table II. Fig. 7 shows the result of experiment. The black solid line shows the reaction force measured by the load cell and the red line shows the estimated perturbation value. It means that the estimated perturbation follows the reaction force closely, validating the assumption that the perturbations are dominated by reaction force.

C. Haptic System

In the experimental result, the perturbation value estimated the reaction force well. In other words, perturbation is mainly affected by the load. Therefore, the estimated reaction force can be used as a feedback by the haptic system for the actual reaction force. The haptic function is realized by current control of DC motor installed in master system shown in Fig. 6. Fig. 8 shows the feature of driving test to grasp a chicken chest tissue. For the haptic function test, two finger tips are driven to perform grasping motion. The operator of the master grip felt the reaction force well during grasping motion and could stop the grasping operation without further closing the tool tip by the perception of grasping the tissue.

IV. CONCLUSION

This paper applied SMCSPO in surgical robot instrument which is a robust control algorithm to overcome its systemic difficulties. Moreover, it was shown that the estimated value by the perturbation observer could be related with the reaction force of the instrument which is difficult to directly measure without a sensor on the instrument tip. Experimental results corroborated the assumption of the relation. Also, this paper tried to use the estimated perturbation value as force feedback signal for haptic system. The generalized evaluation of haptic function was insufficient because of implementation on only one finger grip, but the possibility was ascertained. Therefore, in near future research, haptic function may be extended to up 4 DOF using all axes in surgical robot instrument and has to be evaluated by qualitative analysis.

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