Keynote paper - Real World Haptics Applied to Forceps in Robot Surgery

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***Abstract*— This paper presents the technological achievements in realizing the force feedback in surgical robots. No force sensor is used in sensing the force. Disturbance observer and its variant, reaction torque observer is used to detect the force. Bilateral control is used to transmit vivid sensations from the forceps end to the surgeon.**

***Keywords*—Robot assisted surgery, Bilateral control, Disturbance observer**

I. INTRODUCTION

Technology of mechatronics and robotics is originally developed for production engineering. The word has evolved from the words “Mechanical” and “Electronics”. However, now mechatronics really means a multidisciplinary approach to the real world Engineering product design. Today it is a well known fact that mechatronics is the base of modern robotics. Numerical Control (NC) technology which was introduced in 1970’s has backed the technology of modern manufacturing robot control to a greater extent. Originally, NC gives position servoing, and it is implemented in highly precise machine tools. The basic theory of NC is to obtain high gains, and to suppresses not only static errors but also the dynamic errors. After the introduction of the microprocessor based controls, software based servoing produced more precise position control than before.

Severe price competition among the industrialized nations also influenced for the development of machine tools and its control. To overcome excessive competition and compete against cheap import products, Japanese factories were relocated beyond the sea. As a result, production volumes were increased and export businesses started to flourish at the expense of employment opportunities.

II. CONTACT MOTION BY ROBOT

Highly-developed medical care is really essential to for a country like Japan where the birthrate is declining and the society is aging. Development of the medical care system is two folds that are diagnostic development and the development in the field of treatments. For example, surgical treatments are important for treatments of cancers. At the same time, diagnostics is also important in the early stage of the cancer. In conventional machining tasks, it is essential to have contact motion of machine tools with the work piece. Most of the time contact motion does not require force control or force feedback. But control of the forces in contact motion will be essential in the future. For example, non contact tasks like, paining and welding operations would also be easily controllable if force feedback is present. But force feedback or the sense of touch is essential in places where assembling tasks are carried out by robots. There are several obstacles in realizing force feedback based contact motion control. Accurate detection of the contact force or the torque is difficult as the force sensors are often big and they cannot be placed where the force is to be sensed [1]. Limited bandwidth of the force sensors also hinders the accurate vivid sensation of the force. In this paper, we present a force sensorless technology for the force control of contact motion. This technology can be used in many applications in the future. This paper focuses on the one such important application.

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 large 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.[2] explain the necessity of the MIS. They have discussed, why the doctor at a distance should be a reality in the future.

Force feedback to the surgeon is strongly required by in robotic surgery. Though thousands of surgical robots are used in worldwide, they do not have the ability to present the tactile sensation. Therefore to achieve high level of safety and accuracy in surgical robots, we have proposed and realized a tactile feedback method.

III. Real World Haptics and Minimally Invasive Surgical Forceps Robot System

Information related to two of our senses; the auditory and visual senses, can be transmitted, stored, and reproduced. Telephones and televisions are such examples of the transmission technologies related to our senses. Huge markets have been developed related to the fields of senses. Research of the tactile sensation was started in the 1950s. However, reproduction of vivid tactile sensation has been difficult. The reason is that as shown in Fig. 1 the tactile sensation is inherently composed of bilateral information different from the auditory and visual senses. Because, there is no reaction from the receiver to the sender in the auditory and visual sense of transmission, the information flow is unilateral. On the other hand, the tactile sensation is the bilateral information represented by the law of action and reaction as opposed to the unilateral systems. This requires a strict real time exchange of the information related to the action and the reaction. Therefore, realization of the tactile sensation has been difficult due to the real time commutation problems and the problems associated with the bandwidth. However, when compared to the auditory and visual senses, they are more tolerant to the time-delay.

Most of the controllers that we come across are unilateral controllers. As the name implies, control signal travels from the operator to the actuator. And the operator side is not controlled by the actuators response. This should not be misunderstood as feedback or open loop applications. A unilateral controller may or may not have feedback. Simple example would be a television remote controller. When an operator presses a channel as he wishes, actuation is being done at the TV set. Most of the tele-operation processors are unilateral.

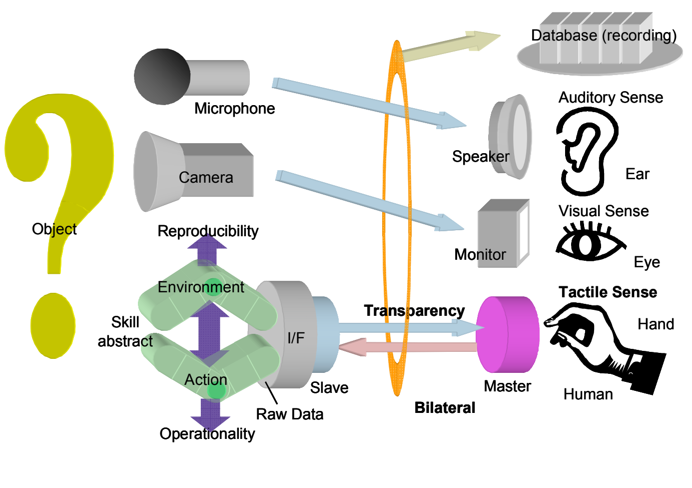

Fig. 1. Human sensors and outside interactions

In order to sense the "sense of touch" remotely, a unilateral controller will not be sufficient. Therefore to transmit the information related to the "action" and "reaction" a bilateral controller should be used. As the name suggests, bilateral controller controls the master and the slave sides from the responses of the slave and master side respectively[3]. These responses are converted as inputs to the master and slave sides. Such that slave side is controlled using the force/position feedback of the master side and vice versa. A major objective of bilateral control is to achieve high transparency. In simple terms, as the word "transparency" means, how well the force position information of the slave side is transparent at the master side[4]. In other words, transparency is the match of the impedance perceived by the operator with the environment [5].

As for the control theory, it has been pointed out that the bilateral controllers can not achieve transparency and stability simultaneously due to the uncertainties of the system and the environment [1]. Therefore, a bilateral system should strike a balance between the stability and the transparency [6][7]. In conventional bilateral control, force sensors are used to detect the force outputs of master and slave. However, as discussed before, force sensors have narrow bandwidth of operation and force sensors can not be placed easily in the place where the force to be measured. Therefore, in this text, reaction torque observer, which is a variant of the disturbance observer, is used as the force sensor [8],[9]. We have been able to transmit vivid sensation from the salve side to the master side [10][11].

Bilateral control is a realization of natural low of motion of two objects. But the input from the operator or the environment response consists elements of disturbance and not only the force. Therefore, to realize a good bilateral system, good disturbance rejection mechanism should be in action. Robust motion control with bilateral control is achieved through the disturbance observer. Acceleration control plays an important role in realizing this motion control.

Bilateral control structure is derived based on the law of action and reaction [1]. When the operator manipulates the system from the master side, slave side has to contact with the environment. However, in applications where master and slave are different, scaling may be used.

The two requirements; realization of the law of action and reaction and the realization of the position control, leads to a contradiction. Realization of the position control is realized by controllers with high stiffness and the law of action and reaction is obtained by controllers with low stiffness. Thus, we need a new controller to realize the two tasks.

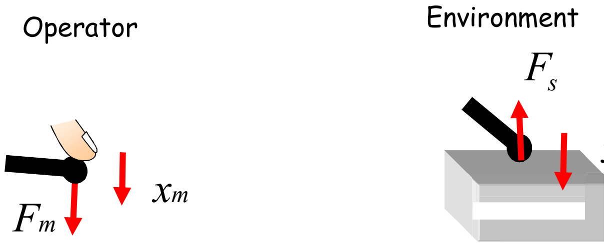

Fig. 2. Basics of Bilateral Control

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

$$x_m - x_s = 0$$
$$f_m + f_s = 0 \quad (1)$$

Here subscript m denotes the master and subscript s denotes the slave.

Realizing the former task is not difficult because it is a position servoing task. On the other hand the latter task is force task. Needless to say, force control of contact motion is not realized in the perfect position controller, and position control of noncontact motion is not obtained in the perfect force controller. (These systems are dual systems described in an equation. The former situation is equivalent to a short circuit with a voltage source, and the latter situation is equivalent to an open circuit with a current source). By using accelerations, which are common variables in (1), the next effective coordinate transform is derived.

The equations in (1) are transformed to (2) and (3) as accelerations[12]. .

$$\ddot{x}_m - \ddot{x}_s = 0 \quad (2)$$

$$\ddot{x}_m + \ddot{x}_s = 0$$

$$\begin{bmatrix} \ddot{x}_c \\ \ddot{x}_d \end{bmatrix} = \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} \cos(-45^\circ) & -\sin(-45^\circ) \\ \sin(-45^\circ) & \cos(-45^\circ) \end{bmatrix}\begin{bmatrix} \ddot{x}_m \\ \ddot{x}_s \end{bmatrix}. \quad (3)$$
$$= \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \ddot{x}_m \\ \ddot{x}_s \end{bmatrix}$$

This coordinate transform is equivalent to the second-order Hadamard transform. By implementing this equation to actual bilateral controllers, Fig. 3 is obtained. This system is called "Acceleration-based Bilateral Control".

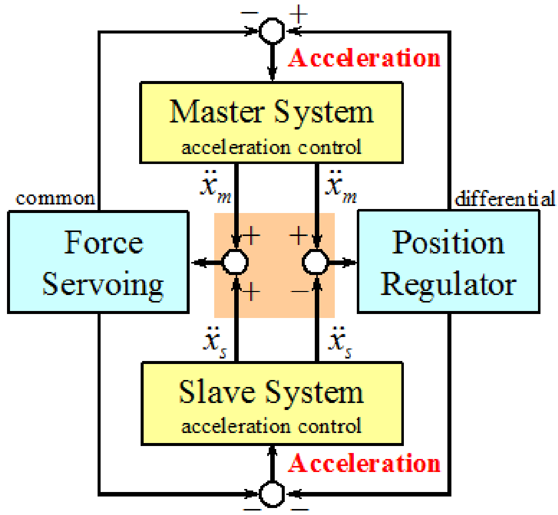

Fig. 3. Acceleration-based Bilateral Control

Acceleration control is a result of robust control of motion control. Then, force controllers and position controllers can be decoupled. It can be said that (3) is transform equation to decouple the tasks. First equation of (3) is a common mode and the second equation is related to the differential mode, finally the master and the slave modes are transformed to common and differential modes[13].

This system is implemented to a surgical forceps robot to realize surgical operations with force feedback. This is depicted in Fig. 3. As suggested before, this system needs only position sensors and force sensors are not used. Examples of implementation are shown in Fig. 5 and Fig. 6.

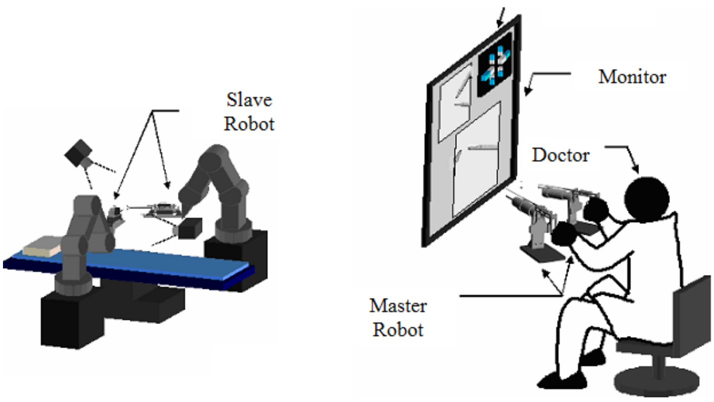

Fig. 4. Minimally-Invasive Surgical Forceps Robot System

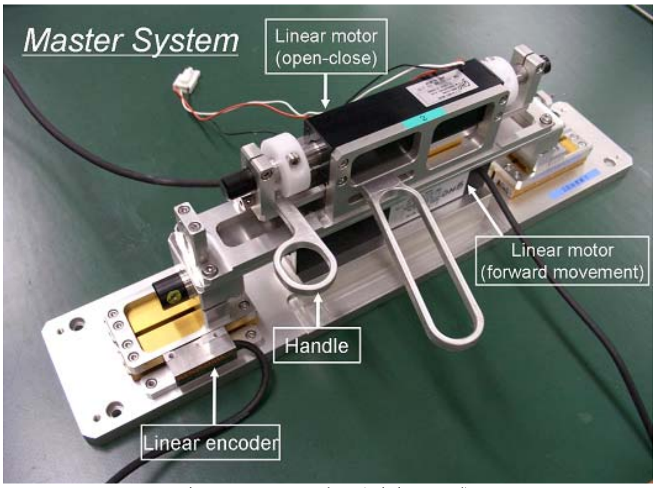

Fig. 5. Master Robot (Right Hand)

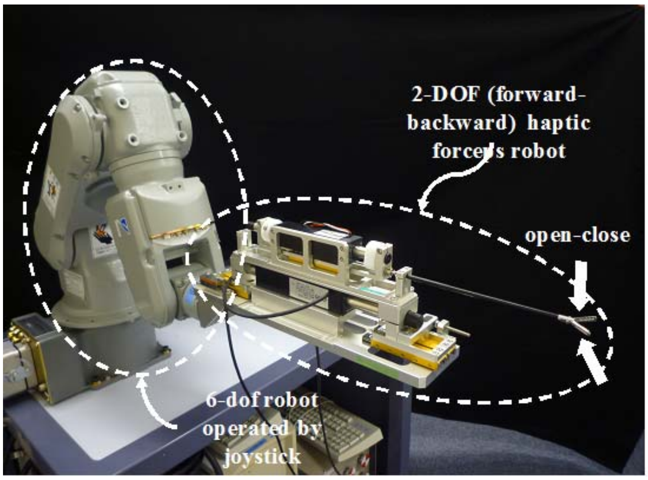

Fig. 6. Slave Robot (Left Hand)

Specifications of this bilateral control system are shown in table 1. The tactile sensation of open-close motion and tip-manipulation can be transmitted.

TABLE 1.
PERFORMANCE OF SURGICAL FORCEPS ROBOT

Evaluation Indices	Performance
Position Resolution	0.01 μm
Force Resolution	0.01 N
Acceleration Response Band	0 – 200 Hz
Mass: Master	300 g
Mass: Slave	200 g
Maximum Force	40 N
Sampling Period	100 μsec

IV. CONCLUSIONS

In bilateral control, the aim is to control the remote manipulator whilst sensing the remote environment. Usually in many applications, the target of bilateral control is to sense the slave environment as it is. However, slave response scaling is used where the sensation felt is not exactly the slave response but a scaled output of the slave. In such applications position, force, impedance scaling might be used. Minimal Invasive Surgery is becoming popular day by day and now the surgery is not only limited to the gallbladder surgery where it was widely used. If the surgeon is kept away from the surgical environment still there are many safety concerns remain even at virtually no time delay. Therefore, even the force feedback in MIS is a "yet to come" technology in commercial MIS platforms. But with the current level of interests and in depth research would eventually lead to a better MIS robots in the near future.

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