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A Force Reflective Master-Slave System for Minimally Invasive Surgery

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***Abstract*— Minimally invasive surgery involves inserting special instruments into the body cavity through tiny incisions in order to perform surgical procedures. In this paper, the design of a robotic master-slave system for use in minimally invasive surgery is discussed. This system is capable of providing haptic feedback to the surgeon in all available degrees of freedom. System design as well as master and slave bilateral control and communication issues are discussed.**

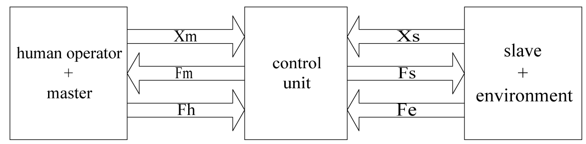

Fig. 1. Haptic master-slave teleoperation

I. Introduction

In the last decade, there has been a growing awareness within medical community of benefits being offered by using robots in various medical procedures [1], [2], [3], [4]. These benefits include possible reductions in cost, improved precision, and even less pain to the patient. For a review on robotic systems aimed at intervention in surgery see [5].

Medical telepresence is a novel approach in robot-assisted medicine which involves performing medical procedures at remote sites using teleoperated robots and has attracted significant interest from the medical profession [6]. In this paper, we focus on a master-slave medical telepresence environment for use in minimally invasive surgery.

A. Minimally Invasive Surgery

Surgery traditionally involves making large incision to access the part of a patient's body that requires attention. This approach is referred to as open surgery. Minimally invasive surgery (MIS) is a cost-effective alternative to open surgery whereby essentially the same operations are performed using instruments designed to enter the body cavity through several tiny incisions of about 1 cm length, rather than one large incision. Instead of looking directly at the area being treated, the physician monitors the procedure via a special camera (endoscope) inserted through one of the incisions. By eliminating the large incision, the trauma to the body, the post-operative pain and the length of hospital stay are reduced significantly. For example, traditional gallbladder surgery requires a six-day hospital stay and up to six weeks for a full recovery and leaves a six-inch scar. However, if operated in a minimally invasive mode, gallbladder patients usually leave the hospital the same or the next day and are fully recovered after a week with the scar barely visible after a few months.

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B. Master-Slave MIS Systems and Haptic Teleoperation

In the robotic MIS systems currently available commercially, e.g. the ZEUS (Computer Motion Inc.) and da Vinci (Intuitive Surgical Inc.) surgical systems, the feedback provided to a surgeon is visual only and no force, torque, or tactile information about the surgical field is provided. It is known that incorporating force feedback into teleoperated systems can reduce the magnitude of contact forces and therefore the energy consumption, the task completion time and the number of errors. In various studies [7], [8], [9], addition of force feedback is reported to achieve some or all of the following: reduction of the RMS force by 30% to 60%, the peak force by a factor of 2 to 6, the task completion time by 30% and the error rates by 60%. Offering these benefits, force feedback can be regarded as a counterbalance to the limited maneuverability of surgical instruments and restricted camera vision in MIS.

In [10], a scenario is proposed to incorporate force feedback into the ZEUS surgical system by integrating a PHANToM haptic input device into the system. In [11], a telesurgery master-slave system that is capable of reflecting forces in three degrees of freedom is discussed. A slave system which uses a modified Impulse Engine (Immersion Corp.) as the master is discussed in [12]. In [13], a dextrous slave combined with a modified PHANToM master which is capable of haptic feedback in four degrees of freedom is presented.

In this paper, the development of a robotic master-slave system with force reflection capabilities that can be incorporated in MIS is discussed. The goal is that (1) the user controls the slave motions via the master interface and (2) tool-tissue interactions at the slave side are fed back to the user through the master interface. This provides a sense of touch to the user.

Figure 1 shows a block diagram of a such a system. The user exerts force F_h on the master interface to move it, thus necessitating a force F_s to be applied on the slave manipulator (to make the slave's position X_s follow that of the master). F_e, the result of the interaction between the slave manipulator and its environment, has to be transmitted to the users' hand (as a force F_m).

II. Master and Slave Design Methodology

The MIS instruments, typically between 25 to 35 cm long and thinner than 10 mm in diameter, are meant to enter the body cavity through several tiny incisions. As a result, the possible degrees of freedom are much fewer than in open surgery and only include pitch, yaw, roll and insertion. We will configure the master interface to have the same degrees of freedom, representing a natural feel to the MIS surgeon.

A. Haptic Master Interface

Based on an extensive review of the haptic devices currently on the market, the PHANToM 1.5A (Sensable Technologies Inc.) was chosen as part of the master interface. It provides six degrees of freedom input control, only three of which are active. In other words, while the PHANToM's end effector can be positioned or oriented arbitrarily in its workspace and registered via readings of six joint angle encoders, force is provided to the user only in the three translational degrees of freedom. This was found to be adequate for our application.

A possible arrangement which uses the PHANToM to allow force reflection at the master side of a robotic MIS system is shown in Figure 2a. As part of the surgeon's console, a laparosopic instrument is passed through a fulcrum and then attached to the PHANToM end point. The PHANToM can be oriented normally or upside down (as shown) and positioned in front of the gimbals (fulcrum) base or on its side (as shown), in order to optimize the instrument's workspace/manipulability and the user's dexterity/comfort. For the configuration shown, the workspace for the instrument tip sweeps at least a pitch angle of $\pm30°$ (up and down), a yaw angle of $\pm40°$ (side to side), a roll angle of $\pm180°$ (rotation about the instrument axis) and a displacement of ±11cm along the instrument axis. Also, the gripping handle angle ranges from 0 to 30°.

The motions of the handles grasped by the surgeon are exactly the same as in conventional MIS, primarily as a result of the restricting port resulting in the fulcrum at the incision. This allows the instrument motions in pitch, yaw, roll and insertion to be registered through the PHANToM. Force reflection, however, is provided by the PHANToM in all of the above except the roll direction.

Roll and gripping are two motions which require additional actuation mechanisms for force reflection. We use a 1-dof haptic mechanism as described in the next part to establish torque and force reflection in the roll and gripping directions, respectively.

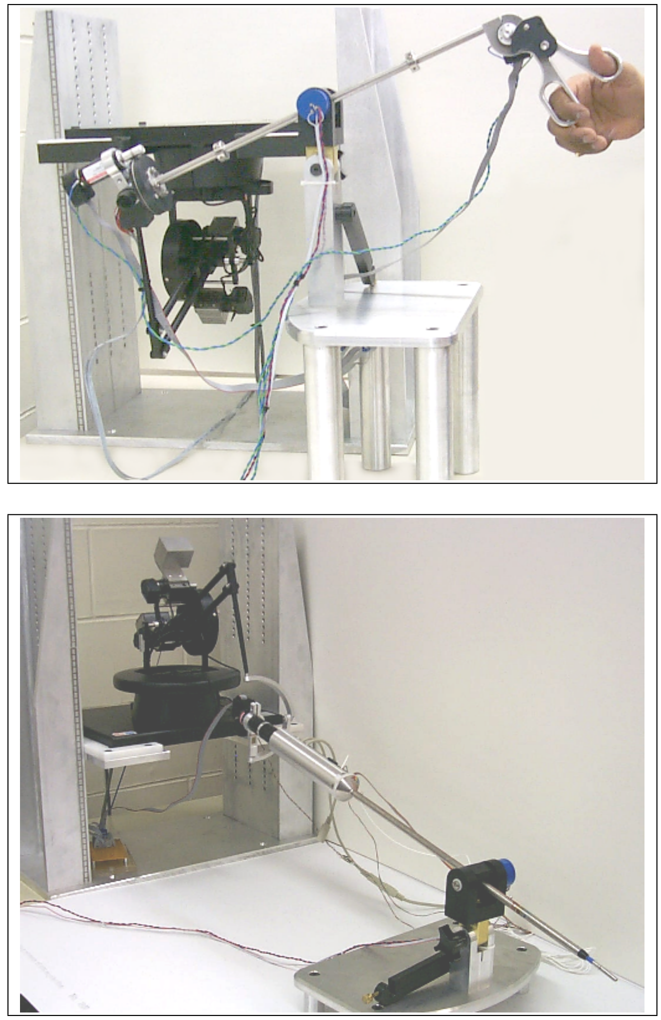

Fig. 2. (a) Master subsystem (top) and (b) slave subsystem (bottom)

Interestingly, the same master can be used equally well in virtual-reality surgical simulation applications. Indeed, the above console can be used in a virtual-reality MIS simulation setting to let a surgeon or a trainee manipulate the surgical instruments and get haptic feedback, as well as graphics feedback, in the form of computer-generated anatomical organs.

1) A single degree of freedom haptic device: First, we consider the desirable features of an ideal haptic device [14]. To reflect forces accurately, there should be (a) very little backdrive friction as friction acts as a kind of additive noise in force reflection, particularly complicating reflection of usually low-magnitude forces due to soft-tissue and instrument interactions, (b) low inertia of the device structure and motors as it creates a bias in force reflection and sets a lower limit on forces that can be reflected and an upper limit on the speed at which the device can respond, (c) very little backlash in the transmission as it introduces a discontinuity in the force transmitted from the motors to the device endpoint and (d) capability for large force reflections in order to create the illusion of a solid obstacle,

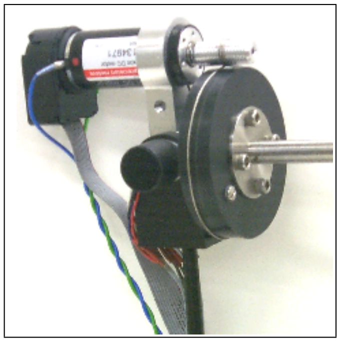

Fig. 3. Single-dof force reflection in (a) the finger loops (left) and (b) the roll mechanism (right)

e.g., a bone in the case of surgical applications. According to [14], 11 N is the force that creates the sensation of a solid obstacle once applied against the user's hand ($F_{\max}$).

A view of the 1-dof haptic mechanism for gripping is depicted in Figure 3a. Due to the requirement of large force reflections, use of a direct-drive motor is not an option. On the other hand, as studied earlier with regard to the PHANToM, gear reductions involve significant backlash while a cogless cable transmission could meet a simple low-friction zero-backlash reduction [14]. Thus, in our 1-dof haptic device, a pre-tensioned cable pinned at both ends of the sector disk and wrapped several times around the motor pulley provides such a transmission. Here the motor is secured to the fixed handle and rotates, through the cable transmission, the sector disk and the other handle fixed to it. Indeed, torque reflections by the motor-cable-disk mechanism simplifies to application of force against the squeezing thumb of the user. An appropriate DC motor from Maxon Motor is selected to guarantee low inertia and low friction in the system. To produce large forces, the stall torque for the motor is the primary specification. Given a desired range of motions, a desired maximum exertable force and a transmission ratio, the necessary peak torque for the motor can be found via

$$\frac{F_{\max} \times (r_{\text{disk}} + L_{\text{handle}})}{\tau_{\text{stall}}} = \frac{r_{\text{disk}}}{r_{\text{mot}}} \tag{1}$$

As shown in Figure 3b, a similar mechanism is also used for force reflection in the roll direction.

B. Slave Robot

As shown in Figure 2b, a PHANToM can also be used in the slave surgical robot to simplify the design and control. Again the PHANToM can be placed behind the gimbals (fulcrum) base (as shown) or on its side, in order to optimize the instrument's workspace. The PHANToM used on the slave side acts merely as a surgical robot as no force reflection is involved. The three last consecutive joints are designed such that their axes intersect at one point, making the inverse kinematics solvable in closed form. Since the PHANToM end point can be placed arbitrarily in 3-D space, the 2-dof gimbals assembly shown in Figure 4d and used to connect the PHANToM end-point to the laparoscopic instrument provides the instrument with pitch/yaw/insertion active degrees of freedom. That the master and slave have the same degrees of freedom as in conventional MIS, eliminates the introduction of new spatial mappings, and consequently a new set of training sessions for MIS surgeons should they want to use this master-slave system. The roll motion is made possible through the introduction of an additional motor as shown in Figure 4a.

As for the fifth degree of freedom, namely gripping, a special mechanism is designed as elaborated in the next section.

1) Surgical grasper mechanism: There are quite a few different tools which can be used in surgery to dissect, grasp, or cut tissue. The components of such tools are generally moved pivotally relative to one another. In MIS where there is a limited amount of space, pivotal motions of the jaws need to be actuated by a linear motion mechanism. Figure 4a shows the linear actuation assembly placed after the roll motor. The parts of this assembly as well as two detachable grasper and scissor tips (Microline Inc.) are demonstrated in Figure 4b. There are three outer, middle and inner tubes with the inner tube being displaced with respect to the outer one by the linear motor (Zaber Technologies Inc.), in order to control the jaws. Hence, the angle of the jaws is easily found from the linear motor position. The logic behind the middle tube will be explained later.

2) Interaction Force/Torque Measurement: In order to measure forces and torques due to tissue/instrument interactions, a multi-axis force/torque sensor can be mounted on the instrument shaft. The sensor has to be mounted between the gimbals and the instrument tip in order not to pick up friction effects caused by the gimbals. Therefore, the multi-axis sensor should be no thicker than 10 mm in diameter. Moreover, it has to be hollow inside to allow the travel of the rod associated with the grasper actuation mechanism. Such a multi-axis force/torque sensor is not available off-the-shelf, and is complicated and and costly to custom-build.

On the other hand, not all six forces and torques need to be measured. Having a 4-dof sensor capable of measuring all torques $\begin{pmatrix}\tau_x & \tau_y & \tau_z\end{pmatrix}$ and one compressional/tensional axial force f_z is sufficient to find all forces $\begin{pmatrix}f_x & f_y & f_z\end{pmatrix}_{\text{tooltip}}$ and the roll moment $\tau_{z_{\text{tooltip}}}$ due to tool-tissue interactions at the instrument tip. Here the assumption is that interactions only occur at the tip of the instrument and not somewhere in the middle.

We have put strain gauges on opposite sides of the surface of the outer tube such that the lateral forces at the tip cause tension in one strain gauge and compression in the other (Figure 4c). These full-bridged gauges register

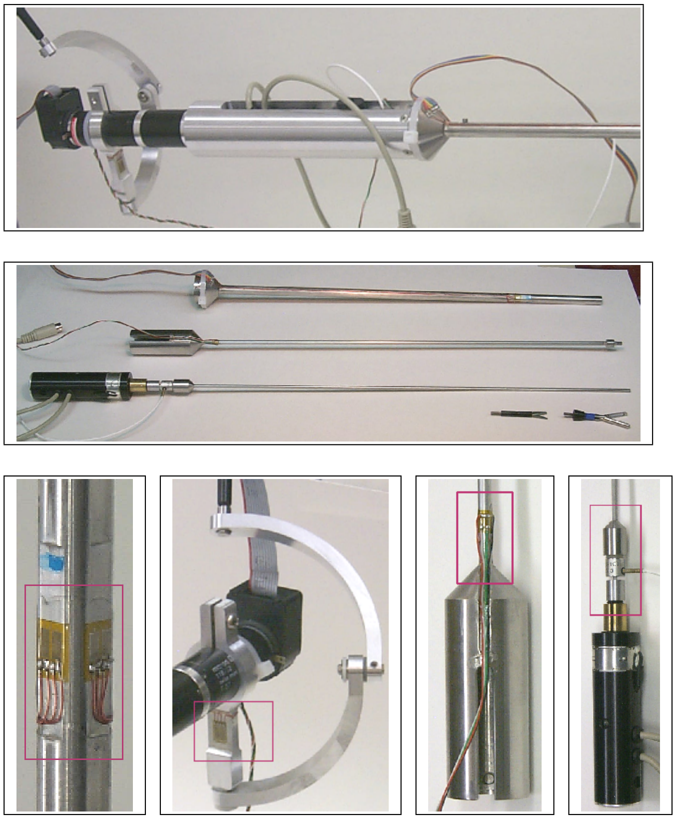

Fig. 4. From top to bottom and left to right: (a) roll motor and linear actuation assembly, (b) details of the tip actuation mechanism, (c) gauges to measure bending moments, (d) gauges to measure the axial forces, (e) gauge to measure the torsional moment and (f) load cell to find grasping or similar forces

two bending moments τ_x and τ_y. Compressional/tensional axial forces which can occur when pushing or pulling on a tissue are registered by the full-bridged strain gauges placed on the 2-dof gimbals (Figure 4d). The torsional moment is measured by the torque gauge placed on the middle tube (Figure 4e) as the detachable tip's outer body threads onto it. The middle tube is made to float between the inner and outer tubes to prevent the force exerted on the inner rod with respect to the outer tube (required to actuate the grasper) from affecting the gauges. Lastly, to measure the gripping force, a load cell is attached between the linear motor shaft and the instrument (Figure 4f). Using this assembly, grasping/cutting/dissecting forces can be found without having to mount sensors on the jaws which can cause sterilization problems for example. Indeed, the interaction forces at the jaws are related through force propagation models to the amount of stress/strain in the rod which is measured by this load cell [15].

III. Bilateral Master-Slave Control and Communication

The most straightforward approach to controlling teleoperated systems in a force-reflecting master-slave mode is direct force reflection where the slave is controlled to follow the measured position of the master while the master is controlled to transmit a force to the user equal to the measured interaction at the slave [16]. Below, the control strategies for both ends of a teleoperated system in a direct force reflection mode are discussed.

A. Slave Trajectory Control

To ensure that the slave-side surgical instrument follows the motions of the master-side instrument in terms of instantaneous position and orientation of the tips, the slave-side gimbals (placed at the incision point) should mimic the motions of the master-side gimbals (placed at the fulcrum) in pitch, roll, yaw and insertion directions. Once the master is manipulated by the user, the instrument tip position is captured by the PHANToM in its reference frame. It turns out that the desired position for the slave PHANToM end-point is found through a mapping on the master PHANToM end-point:

$$P_{\text{slave}} = T_3 T_2 T_1 P_{\text{master}} \tag{2}$$

where T_1 transforms the reference frame of the master PHANToM to the frame of the master gimbals, T_2 translates the slave instrument tip to the slave PHANToM endpoint, and T_3 transforms the frame of the slave gimbals to the reference frame of the slave PHANToM.

We use a neural network as the controller to control the position of the slave end-point. The reason for this is that the dynamics of the PHANToM can vary significantly depending on the interaction forces between the surgical instrument and the environment. As an adaptive scheme, the learning capabilities of neural network controllers help them to cope with varying dynamic behaviors and operating conditions.

We adopt *inverse control* [17] as our trajectory tracking scheme. In inverse control, a neural network learns the inverse dynamics of the system provided the inverse model exists. To do so, first an input u is selected and applied to the controlled system to obtain an output y, and then the neural network is trained to reproduce u at its output from y. Having identified a fairly accurate inverse model of the system, we use *feedback error learning* to shape the closed-loop system.

B. PHANToM Inverse Model Identification

First, we need to show that the inverse model of the PHANToM exists. As shown in [18], the PHANToM dynamics can be written as

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + N(\theta) = \tau \tag{3}$$

where τ is the vector of motor torques (input) and θ is the vector of joint angles (output). If $X = \begin{pmatrix} x & y & z \end{pmatrix}^{\mathrm{T}}$ and J is the Jacobian matrix, then $\dot{X} = J\dot{\theta}$ and $\ddot{X} = J\ddot{\theta} + \dot{J}\dot{\theta} = JM^{-1}(\tau - C\dot{\theta} - N) + \dot{J}J^{-1}\dot{X}$. Now if we choose

$$\begin{aligned} \tau &= MJ^{-1}(u - \dot{J}J^{-1}\dot{X}) + C\dot{\theta} + N && (4)\\ u &= \ddot{X}_r + K_d(\dot{X}_r - \dot{X}) + K_p(X_r - X) && (5) \end{aligned}$$

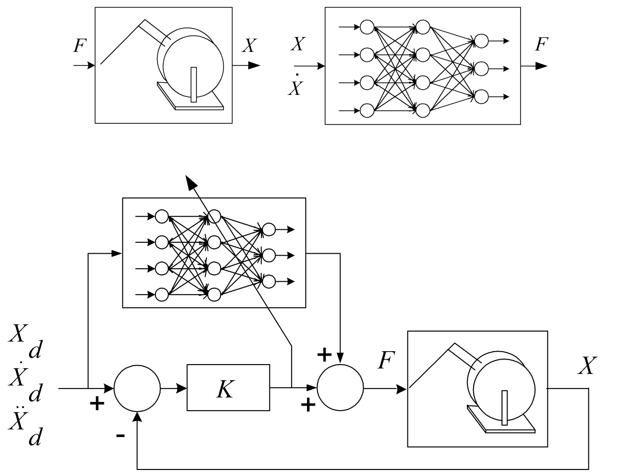

Fig. 5. (a) Inverse model identification of the slave robot (top) and (b) feedback-error-learning position control of the slave robot (bottom)

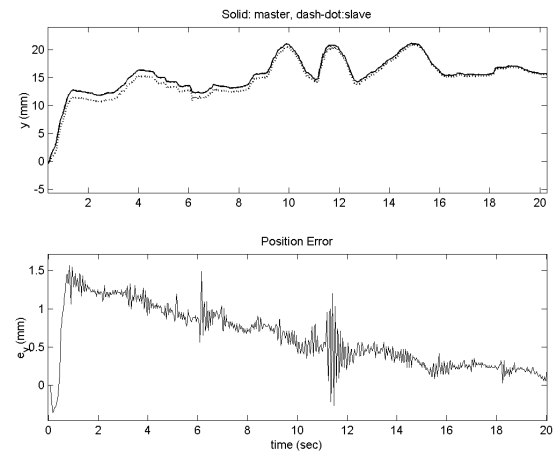

Fig. 6. Feedback error learning control of the slave in presence of a disturbance and arbitrary movements of the master

where X_r is the desired position of the end-effector, it is easy to see that the error e between the desired and the actual positions of the end-effector can approach zero asymptotically through proper selection of the gains K_p and K_d: $\ddot{e} + K_d\dot{e} + K_p e = 0$. Therefore, it is possible to use equations (4) and (5) to generate the control effort (torque) required to drive the PHANToM governed by equation (3) to any desired position. This means that the inverse of the PHANToM exists. Indeed, equations (4) and (5) suggest a controller structure which takes as input the desired and actual positions and velocities and desired accelerations and produces appropriate input torques to guarantee asymptotically zero steady-state positioning error.

Figure 5a shows the architecture used for training a neural network to represent the inverse dynamics of the PHANToM. Inspired by equations (4) and (5), a complete state vector is provided as the input to the network. Indeed, there are six displacement inputs $(x, \dot{x}, y, \dot{y}, z, \dot{z})$ and three force outputs (f_x, f_y, f_z) in the network. A two-layer back-propagation neural network with respectively six and three neurons in the hidden and the output layers is used. The activation function for the hidden layer is a bipolar sigmoid function and that of the output layer is a linear function with saturation limits used to restrict the maximum output force as a safety precaution. The network is first trained offline by input/output data collected through a closed-loop experiment in which arbitrary maneuvers were applied to the master by the user and the slave PHANToM was made to follow it via closed-loop control. The trained weights of the neural network were logged for later use.

1) Feedback Error Learning: In the feedback error learning method, the neural network is used as a feed-forward controller which takes the desired trajectory as the input and is trained by using the output of a stabilizing feedback controller as the error signal (Figure 5b). As the neural network training progresses, the input error to the neural network diminishes, resulting in a greater contribution from the neural network controller to the feedback control.

Here, a simple proportional controller was used to stabilize the closed-loop system. Although online learning is provided to the network, the previously trained weights proved to be very helpful in stabilization in the first stage of learning. Third-order low-pass Butterworth filters were used on the master and slave position readings to avoid training the neural network by a fluctuating error signal. Experiments showed that with this closed-loop control in place, the slave manages very well to track arbitrary movements by the master.

In a more indicative experiment, an additional payload (100 grams) was added to the end-point of the slave PHANToM to investigate the effect of an external disturbance (e.g. the unknown force vector F_e due to a tool-tissue contact). Clearly, this affects the inertia matrix, total mass, and center of mass of the last link and hence the dynamics of the robot. A fixed MIMO control scheme such as *computed torque control* has the disadvantage that disturbances leave an undesirable steady-state tracking error, let alone its dependence on perfect knowledge of the manipulator dynamics which may not be easy to acquire. However, as shown in Figure 6b, the tracking error is asymptotically reduced to zero in the case of feedback error learning control thanks to the online adaptability of the neural controller. Indeed, the effect of the additional mass is neutralized by significant adaptation of the neural weights, particularly those associated with the output layer's unit that corresponds to the vertical component of the force vector.

C. Master Force Control

Once the tissue-tip interaction forces and torques are measured in the local frame of the slave-side surgical instrument ($f_{s_{\text{tip}}}$ and $\tau_{s_{\text{tip}}}$), they have to be applied at the tip of the master-side instrument. The forces and torques required to be applied by the master PHANToM and the roll motor on the instrument tip are then found through the following wrench transformation:

$$\begin{pmatrix} f_{m_{\text{PH}}} \\ \tau_{m_{\text{PH}}} \end{pmatrix} = \begin{pmatrix} R^T & 0 \\ 0 & R^T \end{pmatrix} \begin{pmatrix} f_{s_{\text{tip}}} \\ \tau_{s_{\text{tip}}} \end{pmatrix} \tag{6}$$

where R is the rotation matrix from the master PHANToM local frame to the master-side instrument frame.

D. Master and Slave Communication

Among the advantages of the master-slave teleoperation is the fact that the two ends can be at any distance as long as there is fast communication between them. As a communication protocol, the Virtual-Reality Peripheral Network (VRPN) system [19] provides a device-independent and network-transparent interface to virtual reality peripherals. In our master-slave system, VRPN is used to establish an interface between application programs and the two PHANToMs used as master and slave. Two PCs are used to host the two PHANToMs while a third PC runs the position and force control algorithms. Therefore, the surgical robot can be teloperated by the surgeon sitting on a remote, master console.

E. Conclusions

Improved teleoperation bandwidth and instrument manipulability are some benefits of incorporating force feedback into teleoperated systems. Moreover, force feedback has been demonstrated to result in reduced contact forces and energy consumption, shorter task completion times and fewer errors. We have developed a robotic master-slave system with force reflection capabilities that can be incorporated in MIS. The haptic master interface is capable of reflecting forces in all degrees of freedom available in MIS over a fairly large workspace. The same interface can alternatively be used in virtual-reality surgical simulation applications. On the slave side, MIS allows a bore of no more than 10 mm for the instrument shaft, its tip actuation mechanism and other force/torque measurement devices. The instrument is comprised of three stages to meet these requirements simultaneously. The instrument has detachable tips which can be disposed after use.

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