Development of Micromanipulator and Haptic Interface for Networked Micromanipulation

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Abstract—In this paper, telemicromanipulation systems with haptic feedback, which are connected through network, are proposed. It is based on scaled bilateral teleoperation systems between different structures. These systems are composed of an original 6 degree of freedom (DOF) parallel link manipulator to carry out micromanipulation and a 6-DOF haptic interface with force feedback. A parallel mechanism is adopted as a slave micromanipulator because of its good features of accuracy and stiffness. The system modeling and control of the parallel manipulator system are conducted. Parallel manipulator feasibility as micromanipulator, positioning accuracy and device control characteristics are investigated. The haptic master interface is developed for micromanipulation systems. System modeling and model reference adaptive controller are conducted to compensate friction force, which spoils free motion performance and force response isotropy of the haptic interface. These systems aim to make the micromanipulation more productive constructing a better human interface through the microenvironment force and scale expansion.

Index Terms—Haptic interface, micromanipulation, networked teleoperation, parallel mechanism.

I. INTRODUCTION

IN CONNECTION with the rapid spread of the Internet in recent years, research about computer supported collaborative work (CSCW) technology is performed briskly. It is expected that this network-based technology will simplify the collaboration among distantly connected people supporting human intellectual activities. In the CSCW technology field, the data dealt are only images and sounds, and little attention has been given to the multimodal collaboration including physical contact. We are concerned with networked multimodal collaboration especially those including haptic contacts.

Besides, optical/electronic parts and components new electrical devices, (including mobile PC, PDA, etc.) are becoming smaller and smaller. Consequently, there is an increase in the small-scale manipulation exemplified by the mechanical lenses driver alignment in MD/CD player and small printed circuit board repair work.

Moreover, there is an emergent necessity of a collaboration tool, which allows a better connection among laboratories, offices, and factories in manufacturing (Fig. 1). In addition to the image and the sound, physical communication using haptic device is also necessary for composing such a collaboration tool.

Micromanipulation systems are also studied briskly in recent years and the application to a biotechnology field, a medical field, a nanotechnology field, etc. is expected [1]–[3]. Some micromanipulation systems have been proposed by some researchers [4].

Arai and Tanikawa at MEL Japan developed chopstick-type two-finger manipulator, which is composed by stacked parallel mechanism [5]. They succeeded in manipulating 2-μm grass particle with 0.1 μm positioning accuracy.

Hatamura et al. at University of Tokyo proposed Nano Manufacturing World, which can process using a Fast Atom Beam, and can assemble using micromanipulator with two SEM in the same vacuumed chamber [6]. They demonstrated experimental pick-and-place task using a 100-μm-sized “micro torii (grand gate of Japanese shrine)” under SEM observation.

Although the demand of the above-mentioned task is high in the manufacture and industry field, there are few works and systems, which is focused on the system having the ability to manipulate with several μm accuracy in a few cm workspace. Moreover, there are still few systems, which have the function of force feedback for skillful dexterous micromanipulation in such systems.

Fig. 2 shows our concept figure of our telemicromanipulation systems. In our research, we consider the micromanipulation as an application of the bilateral teleoperation. In this case, the teleoperation is used to connect the micro-workspace with the human workspace. It will solve the scale difference problem existent when teleoperation is performed between human operator and micro objects. These systems aim to provide a more...
comfortable environment for task execution and work efficiency improvement.

In this paper, the kinematics analysis and workspace analysis of the parallel manipulator original mechanism is firstly performed. Positioning accuracy, device control characteristics are analyzed and, the feasibility of the use of parallel mechanisms for micromanipulator is then discussed. The haptic interface with 6-DOF is proposed as a master device for micromanipulator. Proportional differential control (PD) control and model reference adaptive control are applied to the master device and the resulting control characteristic and performance were evaluated. Finally, our experimental results are presented and future directions are discussed.

II. MICROMANIPULATION SYSTEMS

In micromanipulation, visual information of microenvironment is usually taken by microscope. For a human operator, it is a difficult task to manipulate micro objects only for single visual information. Getting 3-D geometry information of microenvironment is important for dexterous manipulation. However it is usually difficult to use two or more microscopes in cost and space constraints and they cannot provide enough information, which supports human dexterous manipulation. The haptic feedback is usually very important in manipulation and it is the reason that haptic interface is adopted to our telemicromanipulation systems.

Fig. 3 shows the configuration of our telemicromanipulation systems. In these systems, the master input device used by the human operator is called the haptic interface. The slave manipulators used directly to perform manipulation are called manipulators. Bilateral teleoperation system is realized with using PHANTOM™ (a commercial haptic interface) or a joystick-type haptic interface (specially developed for telemicromanipulation) as master manipulator [7], [8]. The parallel manipulator with original mechanism is used as a slave manipulator in the teleoperation systems. The slave manipulator and master device systems are connected using Ethernet and they are used to perform teleoperation through the network.

Visual information of microenvironment is taken with a digital microscope and long-focal-distance zoom lens (KEYENCE VH-8000, VH-Z35) and it is sent to an operator site through a network. The magnifications should be changed widely and easily, because in our applications target objects may be manipulated with a few micrometers accuracy in several centimeter workspace. Therefore, the digital microscope with long-focal-distance zoom lens, which has various magnifications from x 35 to x 245, was adopted as the capturing device at manipulator site. Moreover, the lens should be long-focus to avoid collision between the lens and the micromanipulator.

III. SLAVE MANIPULATOR SYSTEMS

A. Parallel Manipulator

Parallel mechanism shown in Fig. 4 is used as the slave manipulator. The main reason for the use of parallel mechanism is its high positioning accuracy. The high stiffness characteristics provided by its truss structure constitutes another reason. The high speed achievable because of the not accumulation of link’s weight in one of the actuators are also another desirable characteristics.

The main drawback is that movable area is narrowed by the linear strokes’ limits and parallel mechanism links collision. In our research, however, this is not a serious problem since our manipulator workspace is enough for micromanipulation.

Our parallel manipulator has a different structure from that used in general Stewart platform (SPF) [9], [10]. This parallel manipulator has sub-links connected to the end of linear drive links. Each two sub-links cross in one point and a platform is supported in these points. It avoids that the workspace becomes narrower because of the restrictions of ball and socket joints. Moreover, using this structure, we were able to arrange the motors (that drives linear motion links) outside of moving ranges of links. Therefore, the workspace of the manipulators is larger than parallel mechanisms, which has actuators in links.

This structure is also able to perform high-speed motion, because motor does not move the motor itself and other heavy components such as ball screws. It is possible to say that the proposed manipulator structure is compact and it allows achieving high-speed motion with high accuracy. The details of workspace of the parallel manipulator are described in Section III-E.

B. Architecture of the Parallel Manipulator

Parallel manipulators with various combinations of chains and joints have been developed by a lot of researchers [11]–[14].

In this section we will denote the joints in the following manner:

• \( P \): prismatic joints;
• \( R \): revolute joint;
• \( S \): socket and ball joints.

In addition, fixed joints to a base are underlined.

Fig. 5 shows that our parallel manipulator is similar to \( PRRS \)-type 6-DOF fully parallel manipulator. The chain sequences \( PRRRR(S) \) and \( PRRR(S) \) make a pair of chains and these chain sequences shares the socket and ball joint \( S \), therefore, this parallel manipulator has asymmetric mechanism. These three chain pairs support the end-effector. Therefore, from the definitions of fully parallel manipulator; a closed-loop mechanism with an \( n \)-DOF end-effector connected to the base by independent chains which have at most two links and are
Fig. 3. Whole composition of telemicromanipulation systems.

Fig. 4. Parallel link micromanipulator.

Fig. 5. Parallel kinematic chains of $P_RRS$-type and our $P_{RRRR(S)}$ combined-type parallel manipulators.

actuated by a unique prismatic or rotary actuator, it is said that our parallel manipulator is not fully parallel manipulator [14].

C. Equivalence to the Fully Parallel Manipulator

Gosselin [15] and Earl [16] have proposed an equation to characterize the “parallelism” of a given manipulator. Earl defined a parallelism index with the formula

$$d = \frac{k}{l - 1}$$

(1)

where $k$ represents the number of independent loops, i.e., the difference between the number of joints with 1 DOF and the number of moving bodies; and $l$ is the number of DOF of the end-effector. This index varies between 0 and 1: 1 characterize fully parallel manipulators and 0 characterize serial manipulators. In our parallel manipulator, the number of rigid bodies is 40, the number of joints is 45, and the number of independent loops is 5. The end-effector DOF are 6. Then

$$d = \frac{k}{l - 1} = \frac{5}{6 - 1} = 1$$

(2)

and, thus, parallelism index is 1. The socket and ball joints $S$ can be divided functionally into three $R$ joints. From another point of view, it can be said that our parallel manipulator shown in Fig. 4 is another equivalent to $P_{RRRS}$ fully parallel manipulator.

D. Inverse Kinematic Analysis

Fig. 6 shows coordinate system adopted for kinematics analysis. Point $O$ is the origin and the criteria coordinate is the base coordinate system. We define each variables and constants in the following manner shown in Fig. 6.

From relations between base joints and end-effector joints in Fig. 6, we get

$$p + Rd_i - \omega_i = l_i z + bs$$

(3)

where $L_i$ is used for $p + Rd_i - \omega_i$

$$L_i l_i z = bs.$$  

(4)

Both sides of equation are squared and because $z^2 = 1$, $s^2 = 1$ and we get the following equation:

$$l_i^2 - 2(L_i \cdot z)l_i + l_i^2 - b^2 = 0.$$  

(5)

This equation is solved for $l_i$ and we get

$$l_i = (L_i \cdot z) \pm \sqrt{(L_i \cdot z)^2 - L_i^2 + b^2}.$$  

(6)

Where, $L_i = (L_{x_i}, L_{y_i}, L_{z_i})$, $z = (0,0,1)$ and using the constraints that the chains sign of square root is negative, we get the following equation:

$$l_i = L_{z_i} - \sqrt{b^2 - L_{z_i}^2 - L_{y_i}^2}.$$  

(7)

Thus, the length of the link $l_i$ is determined by the tip position of the end-effector $F(x, y, z, \phi, \theta, \psi)$. In other words, we can
compute the reference link length \( l_{\text{ref}} \) from the position and posture of the end-effector.

### E. Workspace Analysis

The workspace of the parallel mechanism is limited by
- moveable joint angle range;
- collision between links;
- link stroke length.

The workspace of the parallel manipulator was calculated numerically from the inverse kinematics derived above and constraint condition parameters of our parallel manipulator (Table I). Fig. 7(a)–(c) shows constant orientation workspace of the parallel manipulator, when the posture is fixed as \( (\phi, \theta, \psi) = (0, 0, 0)^\circ \), \( (15, 0, 0)^\circ \), and \( (0, 15, 0)^\circ \). The posture angle is given as Euler angle.

Fig. 7(a) shows that the workspace is almost a column and the top of the workspace is hexagon when the posture of end-effector is \( (\phi, \theta, \psi) = (0, 0, 0)^\circ \). In addition, it is shown that when the end-effector rotates 15° \( (\phi, \theta, \psi) = (15, 0, 0)^\circ \) around \( Z \) axis, workspace becomes narrow with shape similar to triangle pillar. When the end-effector rotates 15° \( (\phi, \theta, \psi) = (0, 15, 0)^\circ \) around \( X \) axis, the center of workspace moves 30 mm along \( X \) axis and there is almost no change of the cross-section area cut with the \( XY \) plane. The workspace of this parallel link manipulator changes with the postures of an effector a lot. When required workspace is sufficiently small, it is not serious problem. In case it performs the work by two or more manipulators, it is necessary to take it into consideration.

### F. System Setup of Slave Manipulator

Fig. 8 shows the structure of the slave manipulator systems. This manipulator’s controller is implemented on a PC with dual Pentium III 500 MHz. The Real Time Linux (RTLinux) is used as the operating system to perform 2.5-kHz sampling time motion control. Input-output using motor, rotary encoder, force sensor are performed by AD, DA, counter, DIO boards connected to an extended bus. As actuators, six similar ac servomotors are installed and 1-mm pitch ball screws are connected to each motor.

### G. Position Control Experiment

Link length reference inputs are used to perform parallel manipulator position control.

Position control experiment is performed using one of the parallel manipulator links. The control parameters of PID controller are tuned, so that the manipulator have high-speed response characteristic with no overshoot. The rated speed of actuator is 3000 r/min in data sheet. Since the pitch of linear link’s ball screw is 1 mm, the linear link speed conducted from the normal rated speed is 50 mm/s.

Fig. 9 shows the response to 1-mm step reference input. The actuator reaches the rated speed by about 10 ms and the position output reaches the reference by about 40 ms. From the evaluation of resultant numerical data, steady-state error of 0.122 \( \mu \text{m} \) was found. The resolution of rotary encoders is 2\( \pi /8192 \) rad and the screw pitch of linear drive links is 1 mm. Therefore, the resolution of linear drive links is 0.122 \( \mu \text{m} \). This steady-state error is equal to the minimum measurable error derived from resolution of actuator’s rotary encoder.

Position control is more important than speed of the motion in the micromanipulation. From the above step response exper-
Fig. 7. Constant orientation workspace. Angles of end-effector are given by Euler angles. (a) \( (\phi, \theta, \psi) = (0, 0, 0)^\circ \), (b) \( (\phi, \theta, \psi) = (15, 0, 0)^\circ \), (c) \( (\phi, \theta, \psi) = (0, 15, 0)^\circ \).

Fig. 8. Slave manipulator systems setup.

iment result, it was verified that the link position control error is less than 0.122 \( \mu \text{m} \). The displacement of each link when the end-effector movement is parallel to \( XYZ \) axis was also calculated. This simulation results are shown in Table II. The initial position of end-effector is \((x, y, z, \phi, \theta, \psi) = (0 \text{ mm}, 0 \text{ mm}, 50 \text{ mm}, 0 \text{ rad}, 0 \text{ rad}, 0 \text{ rad})\).

Linear drive links can be controlled within about 0.122 \( \mu \text{m} \) errors. Therefore, if the required positioning accuracy is 10 \( \mu \text{m} \), we can control it within 10% error. It is also known from the specifications that the mechanism has a repeatability precision of 1 \( \mu \text{m} \). Thus, it is possible to derive from the above data that the manipulator theoretical accuracy is better than 10 \( \mu \text{m} \).
TABLE II
END-EFFECTOR—LINK DISPLACEMENT (μm)

<table>
<thead>
<tr>
<th>(x, y, z) [μm]</th>
<th>link1</th>
<th>link2</th>
<th>link3</th>
<th>link4</th>
<th>link5</th>
<th>link6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.0, 0.0, 0.0)</td>
<td>0.000</td>
<td>0.000</td>
<td>0.072</td>
<td>0.073</td>
<td>0.073</td>
<td>0.072</td>
</tr>
<tr>
<td>(0.0, 1.0, 0.0)</td>
<td>0.315</td>
<td>-0.014</td>
<td>-0.157</td>
<td>0.157</td>
<td>-0.157</td>
<td>0.157</td>
</tr>
<tr>
<td>(0.0, 0.0, 1.0)</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(x, y, z) [μm]</th>
<th>link1</th>
<th>link2</th>
<th>link3</th>
<th>link4</th>
<th>link5</th>
<th>link6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10.0, 0.0, 0.0)</td>
<td>0.001</td>
<td>0.001</td>
<td>2.728</td>
<td>2.728</td>
<td>2.728</td>
<td>2.728</td>
</tr>
<tr>
<td>(6.0, 10.0, 0.0)</td>
<td>3.146</td>
<td>-3.144</td>
<td>-1.571</td>
<td>1.574</td>
<td>-1.571</td>
<td>1.574</td>
</tr>
<tr>
<td>(0.0, 0.0, 10.0)</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
</tr>
</tbody>
</table>

H. Accuracy Evaluation Experiment

Positioning accuracy evaluation of the parallel manipulator is performed. XY-step like path and parallel lines were drawn on the plastic film using the parallel manipulator with needle-type end-effector to estimate the positioning accuracy of the parallel manipulator.

The needle tips of end-effectors were sharpened on a whetstone by hand. Tips curvature radius were about 1–3 μm (Fig. 10), which is enough sharp to draw 10-μm step lines.

Tip of needles and step trajectory by micromanipulator were observed using an optical microscope with CCD camera. The microscopy was calibrated by micrometer driven XYZ stage (M-125.90: Physik Instrumente), of which resolution is better than 0.1 μm.

The step sizes of 10 μm, 30 μm were used. In the cases of 10 μm and 30 μm steps, we could observe the resultant step lines on the plastic plate in Fig. 11(a) and (b). Observed step lines have almost regular intervals and this means 10 μm order positioning precision is achieved.

In the case of 10-μm step, however, step intervals are about 11 μm and in the case of 30-μm step, step intervals are about 32 μm. It is about 10% larger than real reference step. This error is caused by model parameter error of parallel mechanism and it can be decreased by calibration of this parallel manipulator.

Fig. 11(c) shows the resultant photo image of drawn parallel line. Intervals between lines of 10 μm were used. Observed intervals of parallel lines are about 11 μm. In this case intervals are not same as the reference intervals, however, almost regular intervals were observed.

In these experimental results, lines are not strictly straight and are not smooth. The motor controller with finite resolution rotary encoder causes roughness of drawn lines. The sample film deformation by friction between sample and end-effector tip causes deformation of straight lines.

So, it becomes clear that the parallel manipulator can perform positioning 10 μm order accuracy. This positioning accuracy is enough for our target objects like very small electrical/optical parts and its alignment.

IV. MASTER HAPTIC DEVICE

Six-DOF serial link mechanism haptic device shown in Fig. 12 was developed to be used as the master device for micromanipulation systems. We selected parallel link mechanism as a slave manipulator because of its positioning accuracy and high stiffness. Differing from the slave micromanipulator, serial mechanism was selected for the master device because it allows realizing large workspace in a compact way. Translational motions are performed by three linear motors. Z axis linear motor is installed on Y axis linear motor and Y axis linear motor is installed on X axis linear motor.

Rotational motions (roll, pitch, yaw) is performed through the three ac servomotors installed on Z axis linear motors. A 6-axis force/torque sensor (BL Autotech/ NANO sensor) is installed in the roll angle motor. Operator performs manipulation using a grip settled on top of the force sensor. The haptic device workspace dimensions are approximately 20 cm in X, Y, and Z axes, and ±15° in roll, pitch, and yaw.

A. Master Device Systems

Master device PC and I/O system configuration is shown in Fig. 13. Similar system was used in the master haptic control system. RTLinux was used as operating system to control the master at 2.5 kHz.

Kinematics of the master device is simple and clear. Translational motions correspond to displacements of linear motors and posture of roll, pitch, and yaw angles (φ, θ, ψ) correspond to the motor rotation angle.
B. Free Motion Characteristics

If there is no force feedback from the slave device, the haptic device should follow the movement of operator and must move as lightly as possible. Free motion experiment was conducted to verify the system basic properties.

1) PD Controller: Since each linear motor lies at right angles, in the master manipulator, we have the advantage that there is little interference between axes. On the other hand, the rail sides of the linear motors of the $Y$ and the $Z$ axes are installed perpendicularly and there is nonlinear variant friction force. This force has a significant magnitude and depends on the actuators relative positions. Therefore, it is very difficult to model of the whole including the friction effects.

At first, free motion experiment with PD controller was conducted. Parameters were tuned so that there might be no over shoot and a high-speed response might be shown to the step input of force in each axis. Parameters for PD force controller are chosen as $K_P = 12.5$, $K_D = 0.0625$ for $X$ axis, $K_P = 15.6$, $K_D = 0.0625$ for $Y$ axis, $K_P = 4.06$, and $K_D = 0$ for $Z$ axis.

Fig. 14(a) shows the spiral trajectory generated by the human operator using three linear motors for $XYZ$ translational motion. Fig. 14(b) shows correspondent $XY'$ plane trajectory.

The master device trajectory follows spiral trajectory roughly. In $XY'$ plane, master device does not draw smooth circle and some straight lines along $X$ axis can be observed.

Friction of $Y$ axis linear motor is much bigger than friction of $X$ axis linear motor. The friction of $Y$ axis motor changes depending on the relative position between $X$ and $Y$ axes. As mentioned above, if the same force to the $X$, $Y$, and $Z$ axes is inputted, the response to the input of each axis varies according to actuator performance, friction force, system inertia and the isotropy of the response to input force is spoiled. To improve the haptic interface and to provide a natural response for the human operator, the device needs to respond isotropically to operator's force input in all direction.

2) MRAC Controller: To solve the above-mentioned problems, a control scheme based on reference model following was introduced. Examples of such type of control scheme are model reference adaptive control [17], model following control,
model-matching control and the sliding-mode observer based method [18].

Among these methods, model matching control and model following control require the exact modeling of the plant. Since model reference adaptive control could be adapted also for an unknown plant, we selected it for using in our master device.

Transfer functions of the plant, which is linearly approximated and reference are modeled as

\begin{align}
    y_r &= \frac{b_m}{s + a_m} u_a \quad (8) \\
    y &= \frac{b}{s + a} u_a \quad (9)
\end{align}

The control law of the plant is defined as

\begin{equation}
    u = f u_a - q y, \quad (10)
\end{equation}

Where \( f \) is the input gain and \( q \) is the feedback gain. So, the basic loop transfer function is given by

\begin{equation}
    y = \frac{b f}{s + a + b q} u_a \quad (11)
\end{equation}

and then

\begin{equation}
    f = \frac{b_m}{b}, \quad q = \frac{a_m - a}{b}, \quad (12)
\end{equation}
So, the parameter errors may be computed as
\[
\dot{a} = (a + bq) - a_m
\]
\[
\dot{b} = bf - b_m.
\]
Subtracting the differential equation of the basic loop
\[
(y - y_m) + a_m (y - y_m) = \ddot{b}u_t - \ddot{y}. \tag{15}
\]
Setting \( c = y - y_m \), we get the following:
\[
\dot{c} + a_mc = \ddot{b}u_t - \ddot{y}. \tag{16}
\]
Introducing the a Lyapunov function
\[
V = \frac{1}{2} \left( e^2 + \gamma_0 \dot{\theta}^2 + \gamma_1 \dot{\alpha}^2 \right) \tag{17}
\]
where \( \gamma_i \) are positive constants. The following time derivative of the Lyapunov function \( \dot{V} \) may be obtained:
\[
\dot{V} = \gamma \dot{\theta} + \frac{1}{2} \dot{\alpha}^2 + \frac{1}{\gamma_1} \dot{\alpha} \dot{\alpha}
= -a_m e^2 + \left( \frac{1}{\gamma_0} \dot{\theta} + cu_t \right) \dot{b} + \left( \frac{1}{\gamma_1} \dot{\alpha} - cy \right) \dot{a}. \tag{18}
\]

The Lyapunov stability criterion guarantees the global stability of the dynamic system (11) if \( \dot{V} \) is negative semidefinite, which can be ensured by choosing the next adaptive laws
\[
\dot{\theta} = \frac{\gamma_0}{b} \dot{c}u_t \tag{20}
\]
\[
\dot{\alpha} = \frac{\gamma_1}{b} cy. \tag{21}
\]

Using (20) and (21) the necessary gains may be computed and the adaptive law can be realized using the block diagram shown in Fig. 15.

Using three linear motors for \( X-Y-Z \) translational motion, the free motion spiral operation was performed again, now using MRAC controller. Fig. 16(a) shows the resultant trajectory. Fig. 16(b) shows the correspondent \( XY \) plane trajectory.

\[\text{Spiral Trajectory (MRAC Controller)}\]

Fig. 16. Spiral trajectory of master haptic interface with MRAC. (a) 3-D plot of spiral trajectory with MRAC. (b) 2-D plot of spiral trajectory with MRAC.

The \( XY \) plane trajectories of spiral operation with PD controller and MRAC controller are compared. Using the PD controller, some straight lines along the \( X \) axis were observed. On the other hand, it was possible to generate a quasicircular trajectory using the MRAC controller. Introducing MRAC controller, it was observed that the master device force response isotropy was improved remarkably.

In the free motion experiment with PD and MRAC controller, force inputs to master device when performing spiral operation are compared. The Maximum force dimensions are shown in Table III. The force required for moving the master device without control is also shown.

Using MRAC controller, the master device can be operated using 7%–20% of force necessary when using PD controller. From this result, it is clear that free motion performance of the master device was improved.

Moreover, the difference of maximum input force among axes, which was 1.6 N when using PD controller, decreased
to 0.07 N when using MRAC controller. It became clear also from this result that the desired force isotropy characteristic was achieved.

V. NETWORKED TELEOPERATION

Connecting master device and slave manipulator through the network, force feedback bilateral teleoperation system was constructed.

We adopt here a bilateral control methodology for controlling the master-slave systems. Concerning system constitutions for bilateral control, the following four types are well known as representative ones:

- symmetric position servo-type;
- force reflection-type;
- force reflecting servo-type;
- parallel control-type.

Bilateral force-reflecting servo-type controller, which has high operability generally, is adopted in the telemicro-manipulation systems, because the slave manipulator, which manipulates micro objects, should be controlled by position controller.

Considering the scaling between master and slave, the control law of the bilateral force-reflecting servo teleoperation systems is given as the following:

$$
\tau_m = K_m (f_{m\text{ref}} - f_m) \\
\tau_s = K_p (x_{s\text{ref}} - x_s) \\
f_{m\text{ref}} = A_f f_s \\
x_{s\text{ref}} = \frac{1}{A_p} x_m
$$

where $x_m$, $x_s$ are the master and the slave positions and $f_m$, $f_s$ are force given to the master and slave manipulators, respectively. $\tau_m$, $\tau_s$ are force and torque outputs from each actuator of the master and the slave manipulator. $A_p$ is the position scaling factor and $A_f$ is the force scaling factor.

A. Free Motion Experiment

To evaluate performance of slave manipulator controller, networked free motion experiment was performed.

In the system, the master device works with force controller, which use as reference values from slave manipulator system and the slave manipulator system works with position controller, which use as reference position the values from master device system.

Fig. 17 shows the networked free motion experimental results. The solid line represents the positions of slave manipulator and the dashed line represents positions of master device. In this experiment, position scaling factor was defined as $A_p = 20$. Slave manipulator follows master device precisely. A motion delay caused by communication time delay is observed. The round trip time delay of whole systems was about 80 ms.

B. Wall Contact Experiment

The wall contact experiment was conducted using the telemicro-manipulation systems. The force-scaling factor $A_f$ in (24) was set as 0.6. An iron block was fixed in the base of slave manipulator workspace and used as the wall. Hard sponge with a thickness of about 5 mm was stuck on the iron block surface as damper.

The iron block surface is placed so that the wall may become parallel to $YZ$ plane. The slave device was approached from minus $X$ to plus $X$ direction and contacted to the wall.

The top of Fig. 18 shows the position of each device and the bottom of Fig. 18 shows the value of a force sensor. The solid

<table>
<thead>
<tr>
<th>TABLE III</th>
</tr>
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<tbody>
<tr>
<td>MAXIMUM FORCE REQUIRED FOR SPIRAL OPERATION</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>non-controlled [N]</td>
</tr>
<tr>
<td>PD controlled [N]</td>
</tr>
<tr>
<td>MRAC controlled [N]</td>
</tr>
</tbody>
</table>
line and the dashed line represent the slave manipulator position and the master manipulator position, respectively.

There is steep rise of the value of the slave manipulator force sensor at 0.8 [s] and it is shown that an end-effector of the slave manipulator began to contact the wall at this time. At this point there is a little vibration because of time delay between the master and the slave. This vibration is decreased by 2.5 s, it is in a steady-state after that. The force, which is 9 N in the master and 15 N in the slave, is balanced in the steady-state by 4 s. These force value are derived from scaling factor $A_{f}$ in (24).

In this experiment, the force-scaling factor is set to $A_{f} = 0.6 < 1.0$ because of suppression of vibration between the master and the slave. To expand force from microenvironment and feedback to the human operator, the force-scaling factor should be $A_{f} > 1.0$.

VI. CONCLUSION

Telemicromanipulation systems with haptic feedback and parallel micromanipulator, which connected through network, have been proposed. These systems are composed of an original 6-DOF parallel link manipulator to carry out micromanipulation and a 6-DOF haptic interface with force feedback.

Kinematic analysis and workspace analysis of parallel mechanism, which is used as the slave manipulator in the systems, were conducted. The parallel manipulator feasibility as micromanipulator, positioning accuracy and device control characteristics were investigated. As a haptic interface, 6-DOF master device was proposed. Using MRAC control scheme, the friction force was compensated and improved the free-motion performance and the force response isotropy. Whole systems feasibility as telemicromanipulation systems were verified connection the master haptic interface and the slave micromanipulator through network. It follows from that has been said that the master device and the slave manipulator have the necessary performance to perform the micromanipulation.

REFERENCES


