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# A NEW HUMAN-SCALE TELE-OPERATING SYSTEM FOR BIOMEDICAL APPLICATIONS

S. Guo\*,\*\* and J. Wang\*\*

## Abstract

There is an urgent demand for a new human-scale tele-operating system to carry out three-dimensional high-speed micromanipulations for medical and biotechnological applications. In this paper, we propose a new human-scale tele-operating system consisting of three parts: the object, the operating system, and the observation system. The operating system is composed of two parts: the operating robot (the 6 degrees of freedom (DOF) precision parallel micro-mechanism) and the positioning system (the complex macro/micro-system). We designed a precision parallel micro-mechanism as the operating robot with 6 DOF, a movement range of 20  $\mu\text{m}$ , and a resolution of less than 20 nm. The positioning system also comprises two parts: a macromovement stage driven by servomotors and a micro-mechanism stage driven by Piezo actuators. We experimentally evaluated the precision parallel micro-mechanism and complex macro/micro-mechanism. Using our complex macro/micro-mechanism, we evaluated the complex macro/micro-control in one direction, the micro-mechanism complex control with 2 DOF, and the force feedback system. The experimental results indicate that the proposed human-scale tele-operating system can be used to manipulate micro-objects at high speed and with high precision.

## Key Words

Manipulation, complex control, biotechnology, micro-mechanism, Piezo actuator

## 1. Introduction

In biology, micro-machining, and industry, researchers need to manipulate micro-objects in adverse environments, such as poisonous, corrosive, multidimensional, or remote environments. Therefore, three-dimensional high-speed micromanipulation is needed as a fundamental technology for micro-mechatronics and bioengineering applications [1-6].

Recently, bioscience has made great progress through advances in biotechnology, such as in genetic engineer-

ing, cell engineering, and developmental engineering [2, 5-8]. Such research requires micro- and nano-manipulation; mass production; and repetitive, high-speed, and high-precision processing. Consequently, human-scale tele-operating systems have been developed. For numerous potential applications, conventional robotics is insufficient [3]. The main problem is caused by the size of the objects to be manipulated. When the manipulated object is extremely small, such as a cell or an embryo, the necessary system consists of fine mechanisms (macro/micro) and requires a complex fine-motion control system, as shown in Fig. 1. Physical phenomena in the micro-world differ from those in the macro-world. Therefore, a manipulation system must be designed carefully. The key technologies include manipulation, microsystems, visualization, human interface, and automation technology. New approaches must be developed to address the challenge of high-speed micromanipulation.

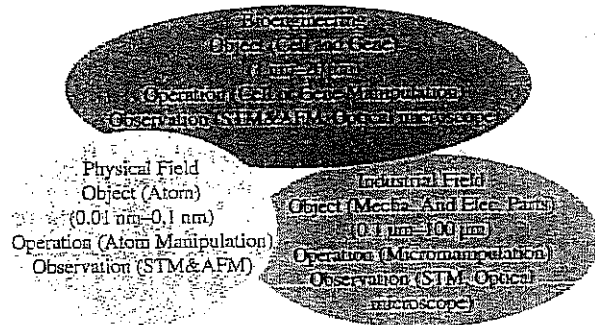


Figure 1. Size of micro-objects.

In most cases, operators manipulate biological objects using micromanipulators while visualizing the process on a two-dimensional image from an optical microscope. However, it is very difficult to operate a micromanipulator in the three-dimensional micro/nano-world, which requires three-dimensional high-speed micromanipulation. Recently, to improve the manipulation method, tele-operating systems have been developed for various purposes [5, 9]. However, these still have some limitations, such as range of movement and fixed resolving power. Our goal is to develop a new human-scale tele-operating system for micro-

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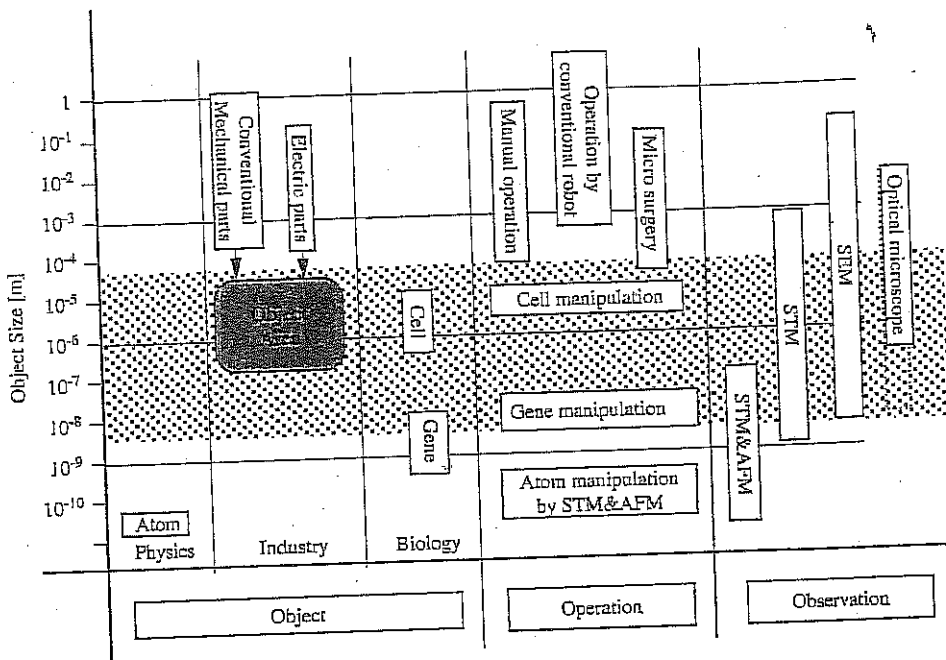


Figure 2. Operation and observation for operating micro-objects.

operations that can manipulate micro-objects of different sizes. Our research project has three goals:

1. To develop a visualization system and make a 3D virtual task model based on this system.
2. To develop a micro-mechanism with high accuracy and multiple degrees of freedom (DOF) for manipulating micro-objects with high precision, and a complex macro/micro-mechanism for positioning micro-objects over a wide operating range.
3. To develop the master arms and control system for manipulation based on human skill.

Here, as part of the proposed human-scale tele-operating system, we developed a parallel micro-mechanism with 6 DOF, a resolution of less than 20 nm, a movement range of 20  $\mu\text{m}$ , and a complex macro/micro-system with a movement range of 25 mm and better than 5- $\mu\text{m}$  precision. In addition, we evaluated these two components experimentally. The results show that the proposed human-scale tele-operating system can be controlled with high speed and high precision via tele-operation.

## 2. Human-Scale Tele-Operating System

Fig. 2 shows the relationship between object dimensions and the operating method. According to the application, we propose a human-scale tele-operating system that consists of three parts: the object, the operating system, and the observation system. The object is located on the workspace table. As the object and workspace are very small, the operating system must have high resolution.

To operate on a human scale, the workspace must be enlarged, and this must be emulated in the observation system. We used an object with 3 DOFs to meet this requirement. We can generate micro- and macro-movement of the object using a complex positioning system and a

micro-operating robot with 6 DOFs [10-16]. The complex positioning system consists of two precision stages: a micro-movement stage driven by a Piezo actuator that can be displaced up to 20  $\mu\text{m}$  and a macromovement stage driven by servomotors that can be displaced up to 25 mm. The proposed human-scale tele-operating system is shown in Fig. 3.

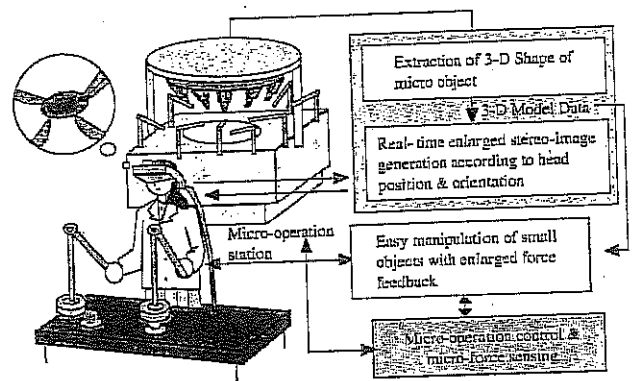


Figure 3. Human scale tele-operating system.

## 3. Design of the Precision Parallel Mechanism

For manipulating micro-objects of different sizes with high precision, we developed a precision parallel mechanism with 6 DOFs, a movement range of 20  $\mu\text{m}$ , and a resolution of less than 20 nm [17-19]. Given that the exact dimensions of the object are uncertain, the movement range and resolution should be adjustable. Therefore, we designed a parallel micro-mechanism as an adjustment robot. As shown in Fig. 2, we wanted to design a mechanism to manipulate micro-objects ranging in size from  $5 \times 10^{-9}$  to  $7 \times 10^{-5}$  m. We wanted the resolution to be adjustable less

han 20 nm. This is a very important point that differs from other research projects [20-24].

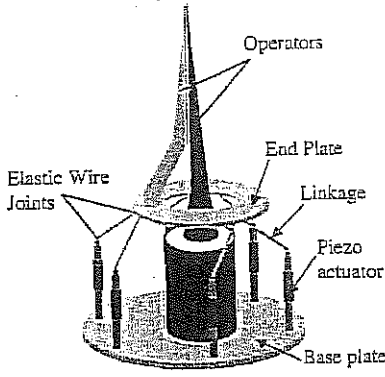


Figure 4. Concept of the parallel micro-mechanism.

The proposed precision parallel mechanism is shown in Fig. 4. It consists of four parts. The first part is the end plate to which the moving part of the operating hand is attached. The second part consists of six linkages. Owing to the large workspace and high resolving power, there are two elastic wire joints at both ends of each linkage, and thus there is no clearance. The length of the links can be adjusted from 33.22 to 38.22 mm in 1-mm steps. The third part consists of six Piezo actuator adapters, designed to enlarge with the same displacement in only one direction when the Piezo actuator extends. The Piezo actuator adapters are fixed on a base plate in a circle; the diameter of the circle can also be adjusted from 29 to 43 mm in 2-mm steps. The fourth part is the base plate used to fix the position of the six Piezo actuator adapters. The operating hands have two parts, one fixed to the end plate and the other to the base plate.

A model of the parallel micro-mechanism is shown in Fig. 5. In the model, we set a fixed O-XYZ coordinate system at point O, and a moving o-xyz coordinate system at point o.

Therefore, the absolute coordinates of point o are  $(0, 0, h + \sqrt{L^2 - (R-r)^2})$ , where  $L$  is the length of a link,  $r$  is the radius of the end platform,  $R$  is the radius of the base platform, and  $h$  is the primary length of a Piezo actuator. As a result, we obtain (1).

$$S \equiv \sqrt{(R \cos|\theta_i - \xi_i| - r)^2 + (R \sin|\theta_i - \xi_i|)^2} \quad (1)$$

In the moving coordinate system, the coordinates of each joint point of the end platform are defined as  $(x_i, y_i, 0)$  where  $x_i = r \cos \theta_i$ ,  $y_i = r \sin \theta_i$ .

Assuming that the movement of the origin of the moving O coordinate system is  $(\Delta x_o, \Delta y_o, \Delta z_o, \Delta \alpha, \Delta \beta, \Delta \gamma)$ , as shown in Fig. 6, the movement of each joint of the upper platform is given in (2):

$$\begin{cases} \Delta x_i = \Delta x_o - y_i * \Delta \gamma + z_i * \Delta \beta \\ \Delta y_i = \Delta y_o + x_i * \Delta \gamma - z_i * \Delta \alpha \\ \Delta z_i = \Delta z_o - x_i * \Delta \beta + y_i * \Delta \alpha \end{cases} \quad (2)$$

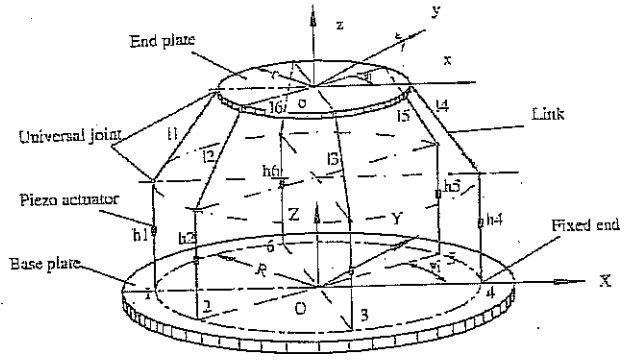


Figure 5. Model of the parallel micro-mechanism.

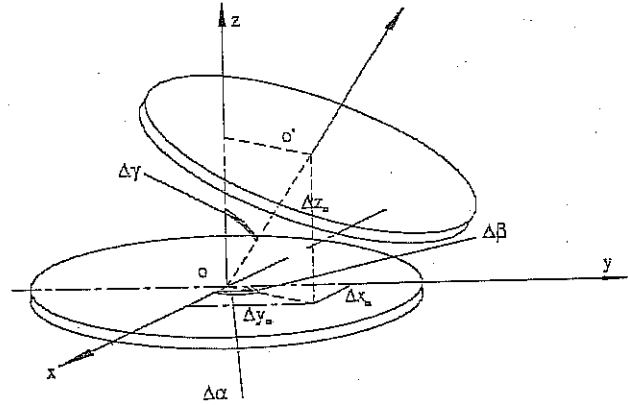


Figure 6. Synthesis of the parallel micro-mechanism.

The absolute coordinates of each point are given in (3):

$$\begin{cases} x'_i = x_o + r \cos \theta_i + \Delta x_o - y_i * \Delta \gamma + z_i * \Delta \beta \\ y'_i = y_o + r \sin \theta_i + \Delta y_o + x_i * \Delta \gamma - z_i * \Delta \alpha \\ z'_i = z_o + 0 + \Delta z_o - x_i * \Delta \beta + y_i * \Delta \alpha \end{cases} \quad (3)$$

where  $z_i = 0$ ,  $x_o = 0$ ,  $y_o = 0$  and  $z_o = h + \sqrt{L^2 - (R-r)^2}$   
Differentiating each side of (3), we obtain (4):

$$\begin{cases} dx'_i = dx_o - y_i * d\gamma \\ dy'_i = dy_o + x_i * d\gamma \\ dz'_i = dz_o - x_i * d\beta + y_i * d\alpha \end{cases} \quad (4)$$

Then, (5) can be obtained as:

$$L^2 = (x'_i - X_i)^2 + (y'_i - Y_i)^2 + (z'_i - Z_i)^2 \quad (5)$$

where  $X_i = R \cos \xi_i$ ,  $Y_i = R \sin \xi_i$ ,  $Z_i = h_i$ ,  $x_i \approx r \cos \theta_i$ , and  $y_i \approx r \sin \theta_i$

Differentiating each side of (5), we obtain following (6) with (1):

$$\begin{aligned} & (r \cos \theta_i - R \cos \xi_i)(dx_o - r \sin \theta_i * d\gamma) \\ & + (r \sin \theta_i - R \sin \xi_i)(dy_o + r \cos \theta_i * d\gamma) \\ & + 2\sqrt{L^2 - (R - r)^2}(dz_o - r \cos \theta_i * d\beta) \\ & + r \sin \theta_i * d\alpha - dh_i = 0 \end{aligned} \quad (6)$$

Propose that

$$\begin{cases} A_i = r \cos \theta_i - R \cos \xi_i \\ B_i = r \sin \theta_i - R \sin \xi_i \\ r s_i = r \sin \theta_i \\ r c_i = r \cos \theta_i \\ M = \sqrt{L^2 - (R - r)^2} \end{cases}$$

Finally, (7) is obtained as follows:

$$\begin{aligned} A_i dx_o + B_i dy_o + M dz_o + M * r s_i d\alpha - M * r c_i d\beta \\ + (B_i * r c_i - A_i * r s_i) d\gamma = M dh_i \end{aligned} \quad (7)$$

Using the parameters  $(\theta, \xi)$  in equation (8), the resolving power is calculated as shown in Fig. 7. If  $h_i \in (0, 20 \mu\text{m})$ , we can obtain the results for two samples, as shown in Table 1. These results show that by changing the parameter length of link  $L$  and the working radius of base platform  $R$ , we can adjust the workspace and the resolution of the parallel micro-mechanism. Based on this, we determined the structure for the parallel micro-mechanism. Fig. 8 is a photograph of the prototype.

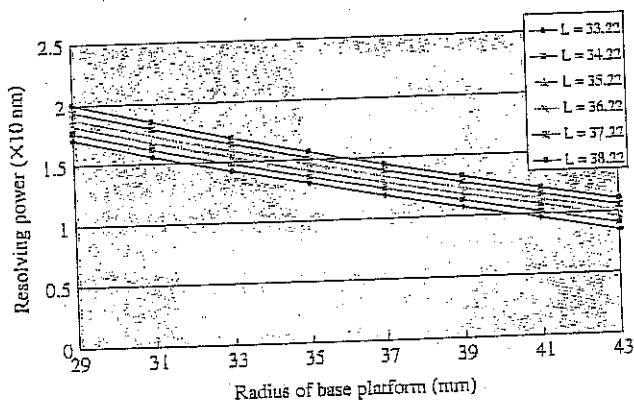


Figure 7. Relation between resolution and changeable parameters.

Table 1  
Calculated Results for Parallel Micro-Mechanism

| Parameter                   | $L = 30.22 \text{ mm}$<br>$R = 45 \text{ mm}$ | $L = 35.22 \text{ mm}$<br>$R = 35 \text{ mm}$ |
|-----------------------------|---|---|
| Approximate workspace (xyz) | $11.8 \times 11.8 \times 20 \mu\text{m}$      | $18.4 \times 18.4 \times 20 \mu\text{m}$      |
| Resolution                  | 10 nm less                                    | 10 nm more                                    |

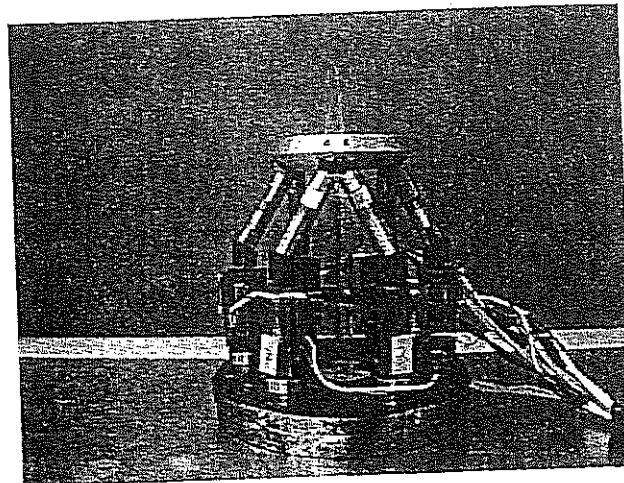


Figure 8. Developed parallel micro-mechanism.

$$\begin{aligned} \theta_1 &= 1^\circ & \xi_1 &= 0^\circ \\ \theta_2 &= 59^\circ & \xi_2 &= 60^\circ \\ \theta_3 &= 121^\circ & \xi_3 &= 120^\circ \\ \theta_4 &= 179^\circ & \xi_4 &= 180^\circ \\ \theta_5 &= 241^\circ & \xi_5 &= 240^\circ \\ \theta_6 &= 299^\circ & \xi_6 &= 300^\circ \end{aligned} \quad \text{As} \quad \text{and} \quad (8)$$

#### 4. Design of the Complex Macro/Micro-Mechanism

The macro/micro-mechanism is used to position micro-objects, as shown in Fig. 9. The capability for complex control is essential in a human-scale operating system. To accurately fix micro-objects over a wide range, we designed the macro/micro-mechanism in two parts. One part consists of three micro-stages driven by Piezo actuators with a movement range of  $20 \mu\text{m}$ . The other consists of two macro-stages driven by servomotors with a movement range of  $25 \text{ mm}$ .

To accurately and stably manipulate micro-objects of different sizes ( $1 \mu\text{m}$  to  $25 \text{ mm}$ ) with dependable precision, we proposed a two-part macro/micro-mechanism consisting of a micro-mechanism and macromovement stages. Fig. 10 is a photograph of the complex system.

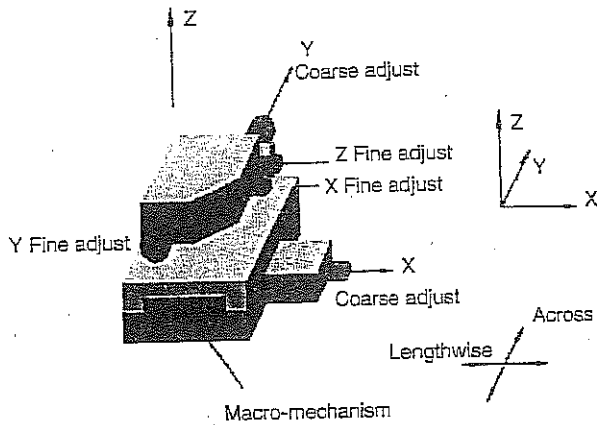


Figure 9. Construction of the macro/micro-mechanism.

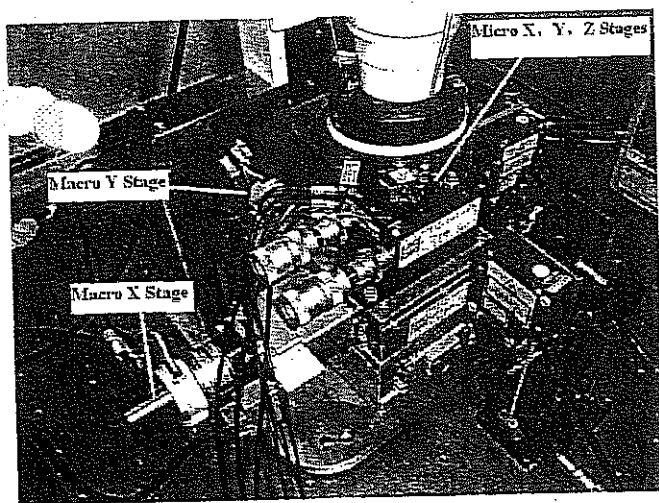


Figure 10. Developed macro/micro complex mechanism.

#### 4.1 Micro-mechanism

In Fig. 9, the top part of the object is the micro-mechanism. This mechanism has been designed with 3 DOFs, which are defined as the X, Y, and Z, stages. Each is driven by a Piezo actuator and has a movement range of 20  $\mu\text{m}$ .

The Piezo actuator driver has a feedback system. The Piezo actuator is driven at voltages between 0 and 75 V. By controlling the driving voltage, we can control the Piezo actuators. In addition, we use a 16-bit controller to control the Piezo actuator driver. Theoretically, this allows a high precision of less than 1 nm. In fact, this precision was very difficult to obtain. Evaluation experiments gave the precision shown in Fig. 11. The experimental results showed that the maximum displacement of the micro-stage in X, Y, and, Z directions is 20  $\mu\text{m}$ , and the relationship between the displacement and the driving voltage was linear. The resulting precision was about 10 nm.

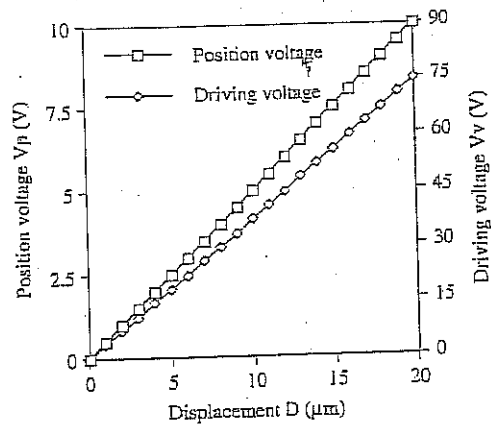


Figure 11. Experimental result for micro-stage.

#### 4.2 Macromovement Stage for the Macro/Micro-Mechanism

The macromovement stage is shown in Fig. 9. It is a 2-DOF mechanism and consists of the X and Y stages. These two parts are driven by servomotors. They have movement ranges of 25 mm as determined by the servomotors. Consequently, with the macromovement stage, the human-scale tele-operating system can manipulate micro-objects over a maximum distance of 25 mm.

### 5. Evaluation Experiments

To examine the precision of our system, we separately evaluated the 6-DOF precision parallel micro-mechanism and the complex macro/micro-mechanism.

#### 5.1 Evaluating the Precision Parallel Micro-Mechanism

In these experiments, we set  $R = 35$  mm and  $L = 35.22$  mm as default values, and the other parameters were set as in (8).

The parallel micro-mechanism is an open structure that uses elastic wire joints, making the method of movement very complex. Therefore, we drove the Piezo actuators in groups. We labeled the Piezo actuators Nos. 1 to 6, and placed them in three groups based on a 3-3 octahedral structure [12]: Nos. 1 and 6 were Group 1, Nos. 2 and 3 were Group 2, and Nos. 4 and 5 were Group 3. We could drive all the Piezo actuators with three voltages in the experiment to determine the displacement of the center of the end plate.

We conducted the following two experiments. In the first, we controlled all three groups of actuators using the same input voltages from 0 to 120 V in 5-V steps. The experimental results are shown in Fig. 12.

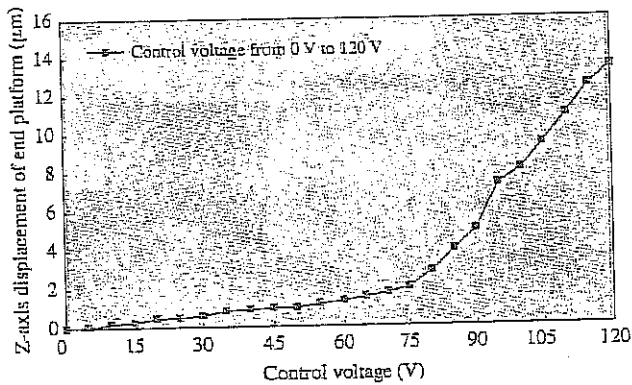


Figure 12. Experimental results by driving 6 Piezo actuators with same voltage.

In the second experiment, we drove the Piezo actuators in each group separately, in the order Group 2-Group 3-Group 1. The driving voltage of each group ranged from 0 to 120 V in 5-V steps. The experimental result is shown in Fig. 13.

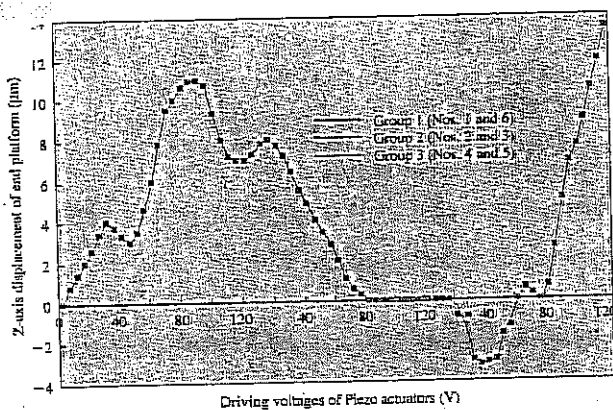


Figure 13. Experimental results by driving 6 Piezo actuators with three groups.

Based on these two experiments, we determined that proposed parallel micro-mechanism can be controlled using six Piezo actuators and that the designed working range can be realized. To avoid hysteresis, we will control the parallel micro-mechanism in a closed loop using gage sensors in future.

## 5.2 Experiments using the Complex Macro/Micro-Mechanism

To control all the stages and to conduct evaluation experiments, we programmed a control application, which included the control program for each stage and evaluation programs based on our hardware system.

In our experiments, a hole with a diameter of 1 mm was used as the object, and we manipulated a wire with a 30- $\mu\text{m}$  diameter. The object was fixed using the macro/micro-mechanism, and the wire was fixed as shown in Fig. 14.

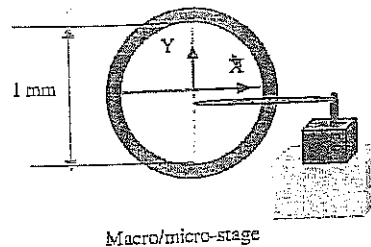


Figure 14. Operating experimental system.

While driving the macro/micro-mechanism, we can clearly observe the movement of the cross on the TV monitor in the macro experiments and can verify the position of the tip of the operating hand. Fig. 15 shows an experimental image photographed using a CCD camera. By contrast, we cannot clearly observe the movement of the cross on the TV monitor in the micro experiments. Therefore, we developed a force feedback system with gages to monitor the micro-mechanism.

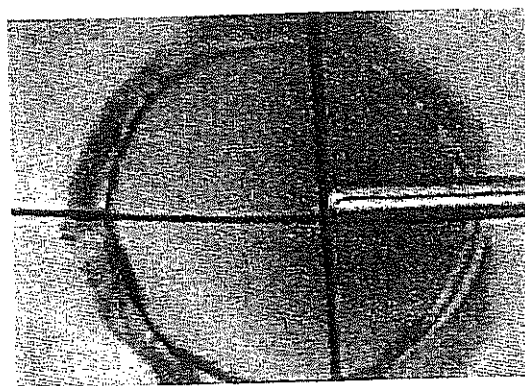


Figure 15. Operating experiment with CCD microscope.

The evaluation program consists of the following two parts.

### 5.2.1 Macro- and Micro-Complex Control in One Direction

Suppose we need to fix a micro-object to a target across a wide range (between 20  $\mu\text{m}$  and 25 mm) with high precision. To do so, we must control the macromovement of the stage over the wide range while precisely controlling the micro-mechanism. In addition, switching between the macro- and micro-controls should be automatic.

Using our algorithm, we conducted experiments to examine the complex control. A typical experimental result is shown in Fig. 16. The platform initially driven by the macromovement stage arrived quickly near the destination. After the platform had arrived within the designated error distance of 10  $\mu\text{m}$ , the macromovement stopped, and the micro-mechanism was activated, until the platform reached the destination. Ultimately, the platform arrived at its destination under the complex control of the macro/micro-mechanism, illustrating the meritorious control of the proposed macro/micro-mechanism.

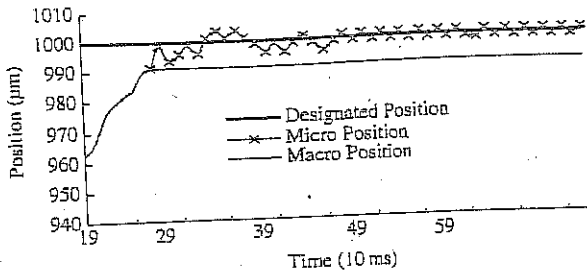


Figure 16. Experimental results for macro/micro complex control.

### 5.2.2 Macro- and Micro-Complex Control with 2 DOF

After demonstrating the outstanding control of the complex macro/micro-mechanism over a wide range, we evaluated the precision of the macro/micro-mechanism. The precision of the micro-mechanism (10 nm) is far smaller than that of the macromovement stage (1 µm). As the control in the Z direction is regulated only by the micro-mechanism, its precision is the same as that in the X and Y directions. Therefore, we only considered the complex control in the X and Y directions using the micro-mechanism.

As shown in Fig. 17, a mouse or a joystick can be used to move the defined moving point (current position) and thus to determine the movement track. Simultaneously, the control software can analyze the error and calculate the actual track from the data provided by the Piezo actuator controller based on a force feedback system. All the tracks are shown in the operating area. For evaluation of more difficult cases, a different called the "rose track" was used (Fig. 18).

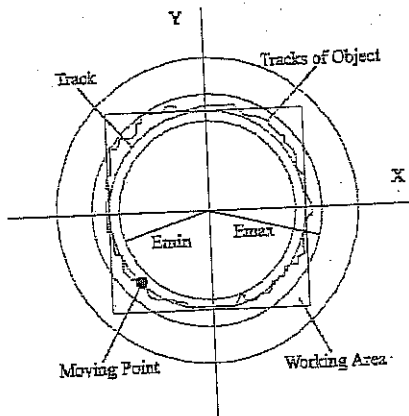


Figure 17. Tracking experiment (circular track).

Our human-scale tele-operating system might have applications in many fields and thus must be operator-friendly. To evaluate the operator-friendly nature of the system, a tracking experiment was repeated by different operators in the same environment, and the values obtained by all the operators were averaged. In each trial, the

track was the same size (20 × 20 µm), and each operator performed 3 to 14 trials using the circular track and 5 to 14 trials using the rose track.

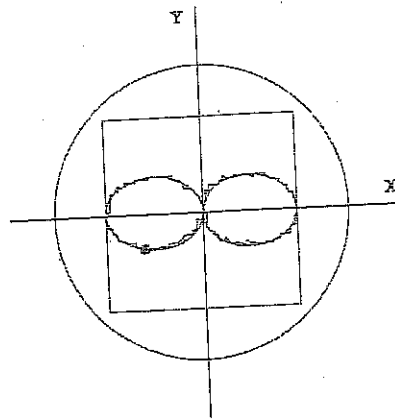


Figure 18. Tracking experiment (rose track).

The results are shown in Fig. 19 (circular track) and Fig. 20 (rose track). The reduction in errors with multiple runs was attributable to reduced operator errors, because hardware errors would not be reduced with multiple observations. The average precision of the macro/micro-mechanism was better than 0.075 µm using the circular track and 0.25 µm using the rose track. Therefore, our system can be used for simple operating tasks. Fig. 21 is a photograph of the operation of the human-scale tele-operating system.

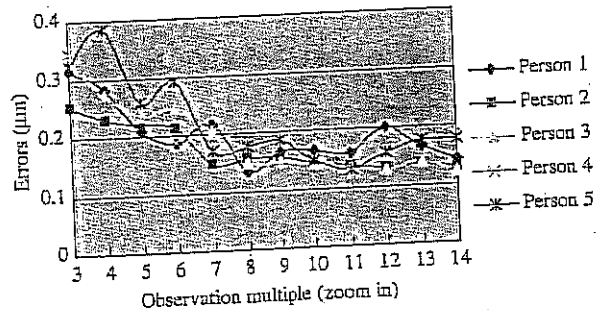


Figure 19. Experimental results (circular track).

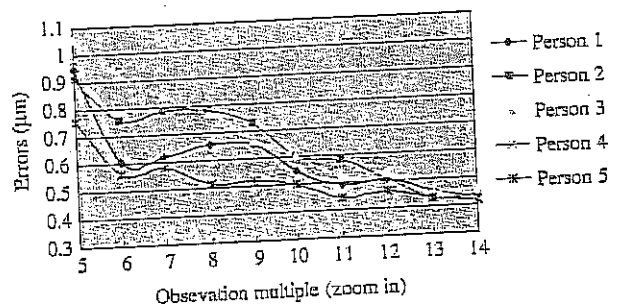


Figure 20. Experimental results (rose track).

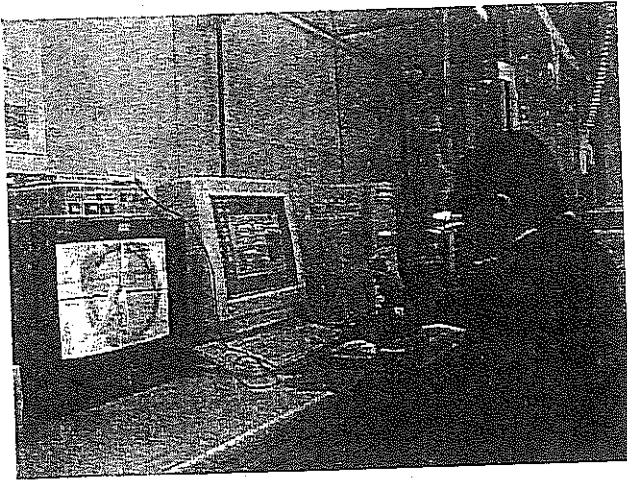


Figure 21. Operating experimental scene.

Larger errors may occur when performing complicated operations owing to the delay time, operating technology, etc. To reduce such errors, we developed an additional force feedback system for the macro/micro-mechanism. In the force feedback system, we pasted one gage to a Piezo actuator in the Z direction (both the X and Y directions have the same movement range as the Z direction, i.e. 20  $\mu\text{m}$ ).

We used an application that we developed to evaluate the system and determined the relationship between displacement and the readable voltage as shown in Fig. 22. Based on the experimental results, the precision of the feedback system was 28 nm, making the complex macro/micro-mechanism very useful.

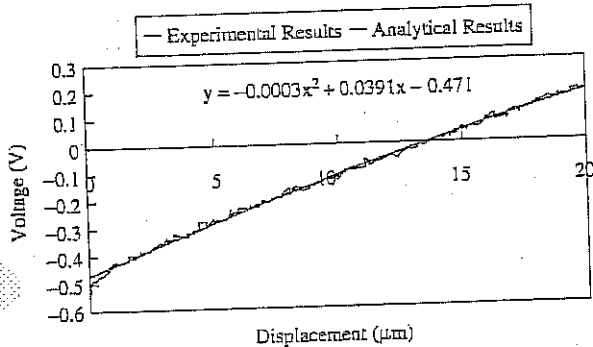


Figure 22. Experimental result for force feedback system.

## 6. Conclusion

In this paper, we propose a new human-scale tele-operating system consisting of three parts: the object, the operating system, and the observation system.

The operating system is composed of two parts: the operating robot (the 6 DOF precision parallel micro-mechanism) and the positioning system (the complex macro/micro system). We designed a precision parallel micro-mechanism as the operating robot with 6 DOF, a movement range of 20  $\mu\text{m}$ , and a resolution of less than 20 nm. The experimental results indicated that the pro-

posed parallel micro-mechanism can be controlled using the voltage applied to the Piezo actuators.

The positioning system also comprises two parts: a macromovement stage driven by servomotors and a micro-mechanism stage driven by Piezo actuators. Using our complex macro/micro-mechanism, we evaluated the complex macro/micro-control in one direction, the micro-mechanism complex control with 2 DOF, and the force feedback system. The experimental results indicated that the proposed complex macro/micro-mechanism can be used to precisely position micro-objects.

We demonstrated that the current operating robot and positioning system of our proposed human-scale tele-operating system can be used to perform simple tasks at high speed and with high precision. In the future, we will develop an operating skill model based on human skills, and will incorporate more force feedback control based on a task model, for application to cell biology.

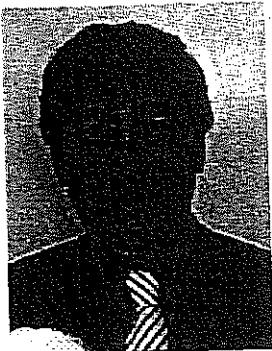
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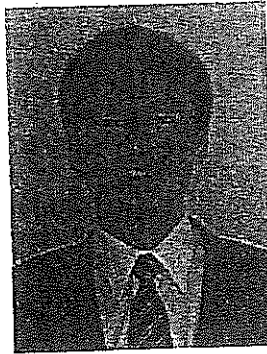
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