

A Neurosurgical Robot for the Deep Surgical Field Characterized by an Offset-Type Forceps and Natural Input Capability

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Abstract

This paper describes a neurosurgical system for the deep surgical field. The developed system has 2 main features, as follows. (1) The previous neurosurgical system developed by the authors' group has straight-type forceps. With straight forceps it was difficult to see the deep surgical field because the drive mechanism of the forceps and the camera-equipped microscope interfered with each other. In this paper, therefore, offset-type forceps have been developed to improve the quality of the visual information obtained from the deep surgical field, at a depth of up to 170 mm. (2) The operability of the master manipulator has been improved by adopting a mechanism in which the commanded orientation and position of the slave manipulator are obtained from the natural wrist and arm motions, respectively, of the surgeon.

1. Instructions

Robotic surgery is characterized by the following advantages. (1) It is possible to see diseased regions that normally are obscured by internal organs or bones. (2) It makes it possible to conduct surgical operations in narrow spaces and behind organs with precision and high accuracy, which is difficult using conventional surgical techniques. (3) It enables the performance of teleradiology and telesurgery.

Neurosurgery is a difficult task because the surgical operation is conducted in a narrow space. The difficulty of neurosurgery in the deep surgical field is further increased because the approach path to the surgical field is limited. Therefore, the development of a computer-assisted surgical system, which can be used in the deep surgical area of the brain, is highly desirable.

Viewing the visual field during an operation is one of the crucial requirements for developing a computer-assisted neurosurgical system. Interference between the forceps and the microscope in the system originally developed by the authors' group [1] limited visibility. Therefore, offset-type forceps were developed to avoid the interference between the forceps and the microscope. Several forceps with a small diameter have been developed by other researchers. They can bend at the tip of the forceps. However, they do not

solve the interference problem with the optical axis of the microscope.

2. Related Work

NeuroArm and NeuRobot have been developed as neurosurgical robots. The key feature of neuroArm is MR-compatibility [2]. For the mechanism, however, conventional type-forceps are used in the system. NeuRobot can perform precise operations with 3 sets of 3 d.o.f. manipulators with a diameter of 3 mm, located inside a tube with a diameter of 10 mm [3]. However, the workspace of the robot is too small, for example, to remove a tumor. Moreover, Harada, et al. have developed a spatula type forceps with 2 d.o.f. using ball joints with a diameter of 2.4 mm for microsurgery [4]. Simaan, et al. developed a snake-like small forceps with a diameter of 4.2 mm [5].

3. Overview of the Developed System

The neurosurgical robot described in the paper comprises master and slave manipulators. The slave manipulator follows the input orientation and position information of the master manipulator. The magnification ratio for the orientation is 1/1 and the magnification ratio for translation is 1/10 to 1/20. Therefore, any trembling of the operator is reduced at the slave manipulator. The master and slave manipulators are controlled by separate, real-time controllers. Telesurgery is also possible using the developed system.

4. Slave Manipulator

4.1. Requirements of Forceps Considering the Visual System

Precise motion is obtained by the mapping ratio from the master manipulators to the slave manipulators. The drive system of the forceps and the camera-equipped microscope interfere with each other when the camera views the surgical field from a perpendicular direction, because the axis of the driver and the forceps long axis are located in the same line

when straight-type forceps are used, as shown in Figure 1. Therefore, it is desirable to develop forceps with a configuration that will improve the acquisition of visual information.

The forceps long axis and the camera axis should be close to each other. The following methods can be proposed for this purpose. (1) Space for the camera can be reserved by increasing the length of the forceps. (2) The drive axis of the forceps can be offset from the optical axis of the camera.

Lengthening the forceps resulted in a high level of vibration when the forceps and the camera touched. Therefore, offset-type forceps were adopted in the developed system. The amount of offset was set as 100 mm, considering the necessary clearance for the camera. The length of the inserting part was determined to be 150 mm to allow access to the deep part of the brain, as shown in Figure 2.

4.2. Development of the Offset-Type Forceps

The following 4 methods were considered for the offset-type forceps: (1) Using a pulley, as shown in Figure 3(a), (2) Using a spring, as shown in Figure 3(b), (3) Using a bevel gear, as shown in Figure 3(c), and (4) Using a universal joint, as shown in Figure 3(d).

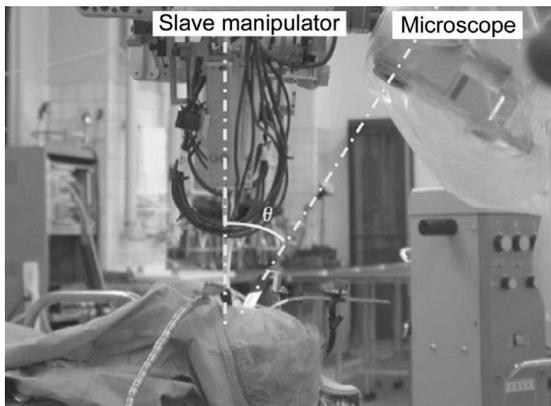


Fig. 1 Relationship between the slave manipulator and the microscope with a camera

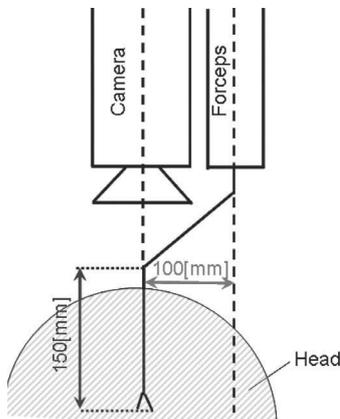
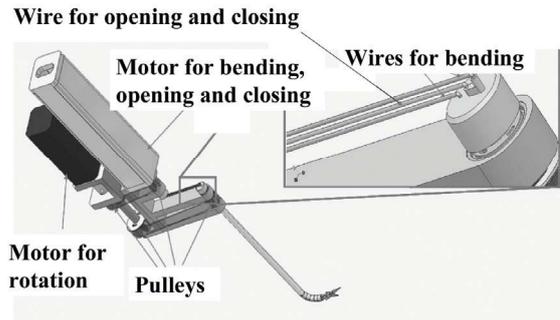
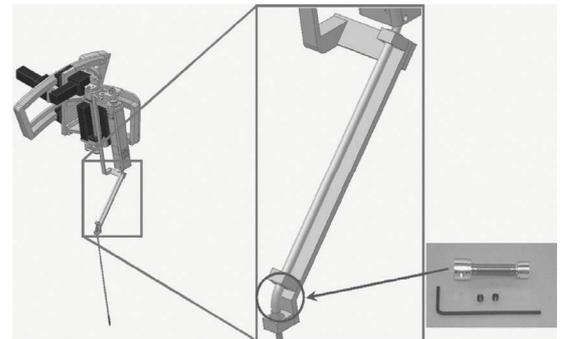


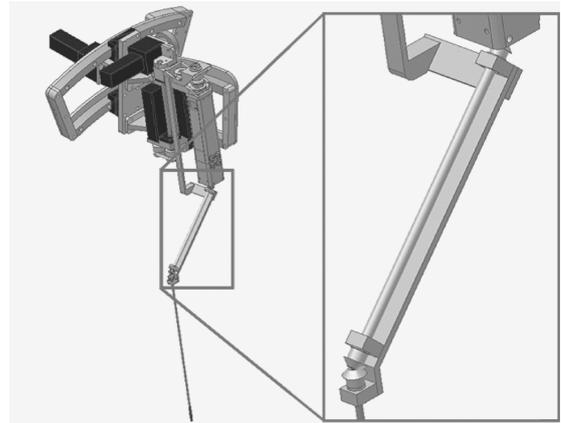
Fig. 2 Concept of offset forceps



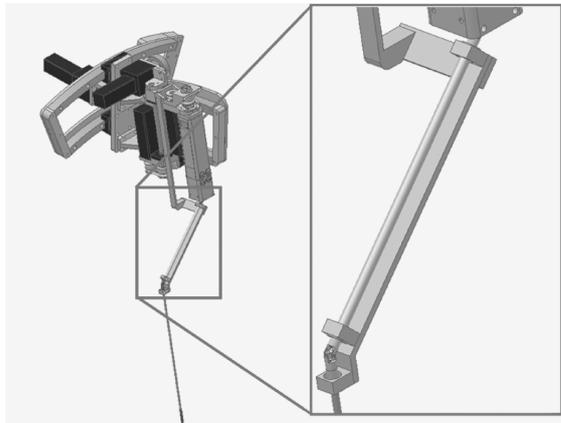
(a) Method using a pulley



(b) Method using a spring



(c) Method using a bevel gear



(d) Method using a universal joint

Fig.3 Mechanism for offset forceps

as shown in Figure 3(d). Among these, methods using a pulley, spring or bevel gear are not appropriate because the incorporation of wires, which are used for the bending and opening/closing of the forceps tips, is difficult. There is a possibility that the variance of wire length, while rotating around the long axis, may cause unexpected bending and opening/closing. Such behavior is expected to reduce the operability and the safety of the system.

Following the discussion above, by using a universal joint, as shown in Figure 4, we propose a mechanism in which the wire length does not change while the forceps tip is rotating around its long axis. A tube, which is attached at the end of the universal joint, rotates around the long axis without changing the tip position while rotating, as is the characteristic of the universal joint. The angle ratio between the input and output axes is 1:1. Therefore, the length of the wires, which are used for bending and opening/closing of the forceps tip, is maintained constant even though they are not passing through the center of the universal joint when the input and output axes are oriented parallel to each other, by using 2 universal joints. In the system, the universal joints act as a guide for the wires, as well as transmitting rotational torque and motion.

The position of the wires in the inclined cylinder is determined by the mechanical parts at points B and E in Figure 4. The mechanical parts at points B and E incline following the rotation around the axis. A cone-shaped hole is adopted for these parts to make their operation independent of their inclination angle.

By adopting universal joints, the wire length is maintained mechanically constant without controlling its length, for example, by using a motor. This increases the stability of the system.

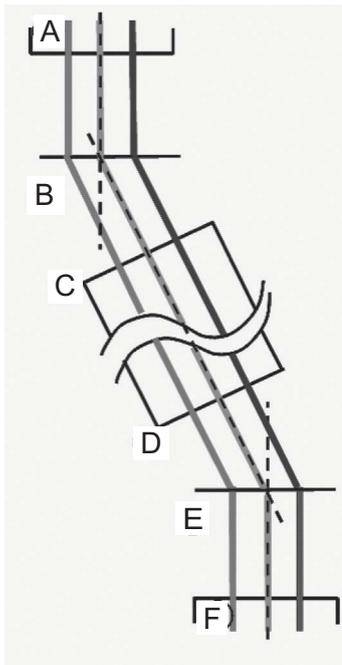
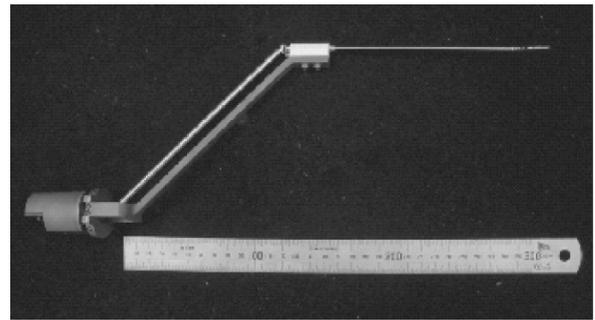


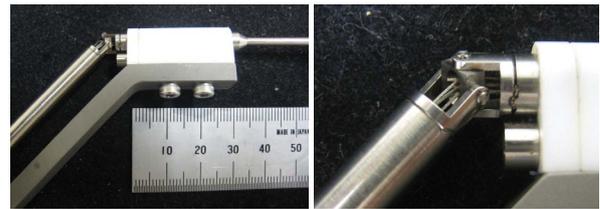
Fig. 4 Basic design of the offset type forceps

4.3. Implementation of the Offset Type Forceps

Figure 5(a) shows an overview of the developed offset-type forceps. Figures 5(b) and 5(c) show the angle conversion part and the universal joint with wire guide, respectively. The developed slave manipulator with offset-type forceps and a visual information acquisition system is shown in Figure 6.



(a) Overview of the offset type forceps



(b) Angle conversion part (c) Universal joint with wire guide

Fig. 5 Developed offset type forceps



Fig.6 Developed slave manipulator

4.4. Evaluation of the Offset Type Forceps

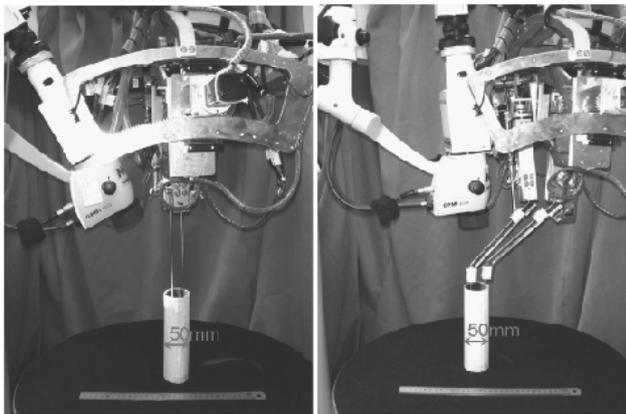
This paper proposes a new mechanism for offsetting the forceps axis and for reducing the diameter of the forceps. The diameter of the forceps is 2.5 mm. Consequently, the workspace of the camera-equipped microscope is increased. Furthermore, the optical axis of the microscope comes close to an axis perpendicular to the opening in the skull used for craniotomy. In the experiment, a scale was mounted in a cylinder with a diameter of 50 mm to allow measurement of the observable depth. Figure 7 shows the experimental setup.

Visual information was obtained to a depth of approximately 70 mm when using the straight-type forceps, because the microscope had to be set at an inclined angle, as shown in Figure 8(a). The visual information at the base, which was located at the depth of approximately 170 mm, was obtained because it was possible to locate the forceps axis and the camera axis in a straight line, as shown in Figure 8(b).

5. Master Manipulator

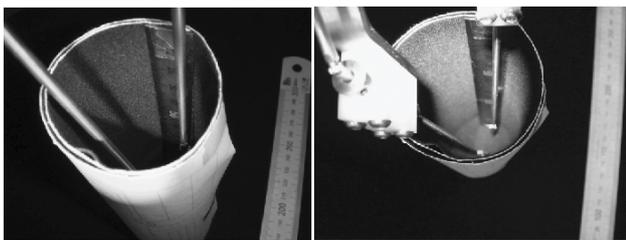
5.1. Mechanism Design of the Master Manipulator

In this paper, we assume that an operator inputs the posture and position naturally by the motion of wrist and arm (upper and forearm), respectively. Moreover, the input parts for the rotational and translational motions (position)



(a) Straight type forceps (b) Offset type forceps

Fig. 7 Experimental setup



(a) Straight type forceps (b) Offset type forceps

Fig. 8 Visual information acquisition

are separated to increase the simplicity of control.

First, the motion at a human wrist was investigated. The human hand has bend and rotation freedom as shown in Figure 9. A gimbal mechanism was adopted to obtain the wrist motion. The singular point, called the gimbal lock, is avoided by allocating the degree of freedom that causes the singular point to the radial and the ulnar flexions, whose motion ranges are small, and by setting the initial orientation appropriately.

Second, the arm motion was analyzed. In the analysis, it was assumed that the motion is 2-dimensional in the vertical plane. Figure 10 shows the relationship between the hand position and the orientation of a device, which is held by the hand, while moving the arm. In the figure, the start position and the orientation of the vector show the hand position and the device orientation, respectively. Generally, the orientation of the device held by the hand varies following

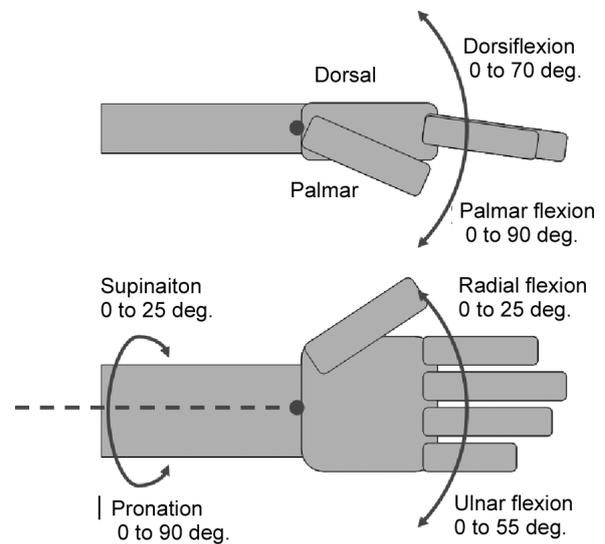


Fig. 9 Hand posture

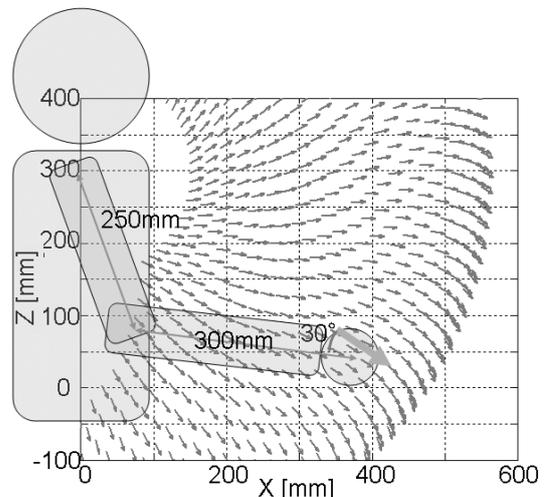


Fig. 10 Working area of arm

the position input by the arm motion. The design principle is, therefore, that the basic attitude of the orientation input follows the motion of the arm while inputting positions.

In order to operate with hands on the table, a linkage to approach the intended area from above was proposed as shown in Figure 11(a). The working area of the linkage can correspond to that of a surgeon's arm by selecting appropriate parameters. However, the orientation input does not correspond to the posture of the surgeon's hand, as shown in Figure 11(b). On the contrary, the orientation of the forearm is similar to that of link L1 in Figure 11. The orientation input part is caused to move parallel to L1 by introducing a parallel link mechanism, as shown in Figure 12(a). Consequently, the angle between the orientation input part and the position input part does not change when a surgeon moves the forearm without moving the wrist. The attitude of the hand and that of the posture input part become similar to each other, as shown in Figure 12(b).

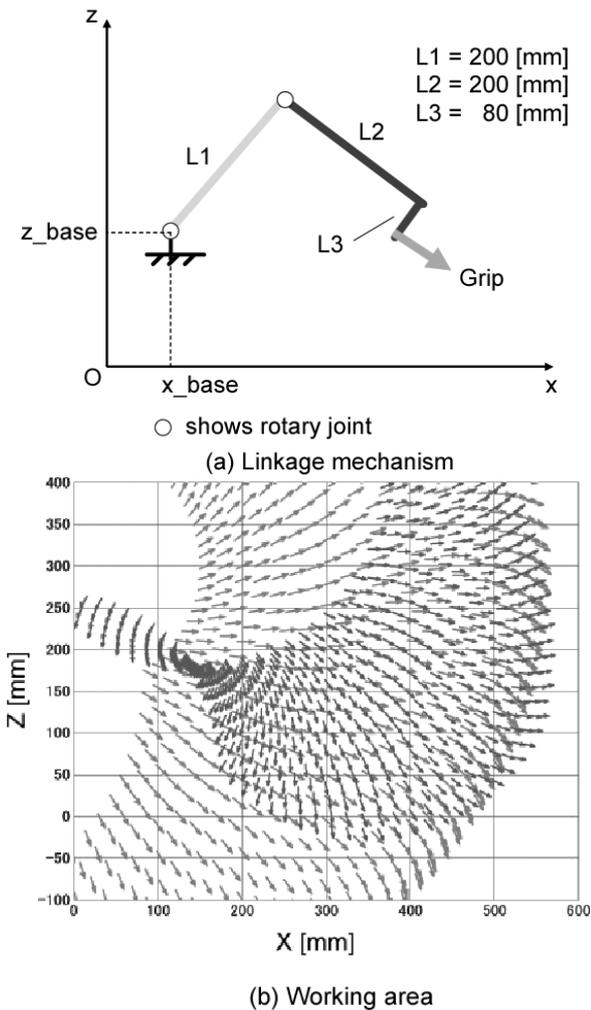


Fig. 11 Example of simple link

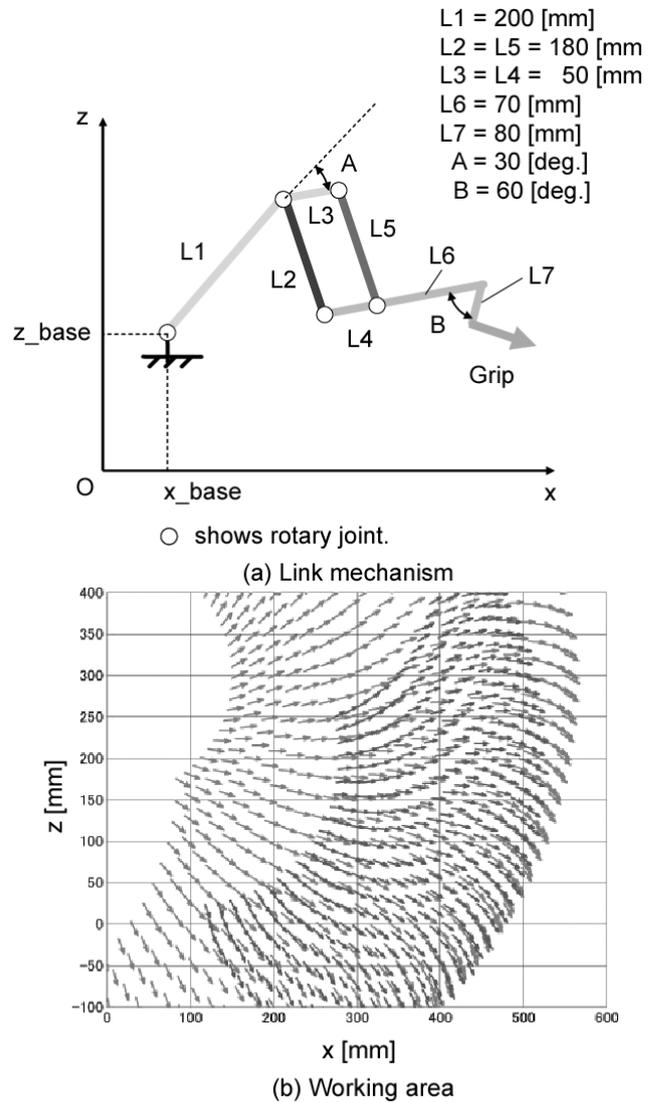


Fig. 12 Proposed link mechanism and working area

5.2. Implementation of Master Manipulator

Figure 13 shows an overview of the developed master manipulator. The total weight was reduced by using PEEK (polyetheretherketone) and aluminum alloy materials. The rotary encoder at each joint measures the joint angle to calculate the position and orientation of the master manipulator. DC motors are mounted at the translational motion input part and the grasping part to feedback the detected force and to compensate for the weight of the master manipulator.

5.3. Evaluation of the Master Manipulator

Manipulability of the master manipulator during

translational motion was measured to evaluate the operability of the developed system. The manipulability is calculated as $w = |\det J|$ where J is the Jacobean of the manipulator. Figure 14(a) and 14(b) show the manipulability of the newly developed and conventional master manipulators, respectively. Details of the conventional

master manipulator are described in [6]. It is clear that the operability of the master manipulator was enhanced.

6. Conclusions

A neurosurgical system with high operability in the deep surgical field was developed. Concretely, offset-type forceps were developed to obtain visual information in the deep surgical field, for example, at a depth of 170 mm. Master manipulators with natural input capability were developed. The experimental results confirm the increased operability of the system.

7. References

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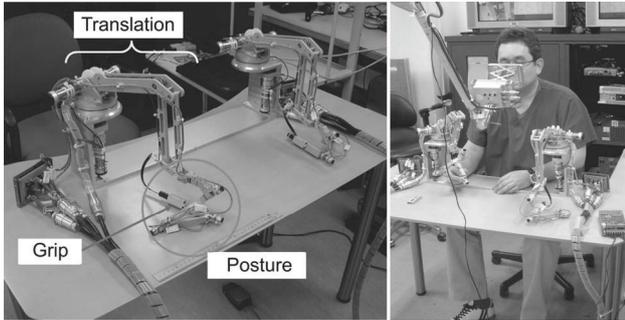
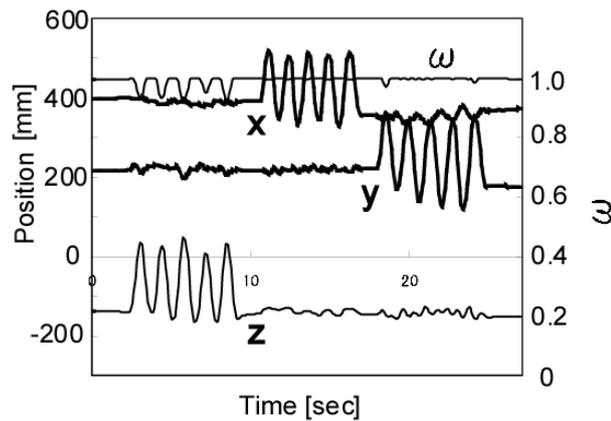
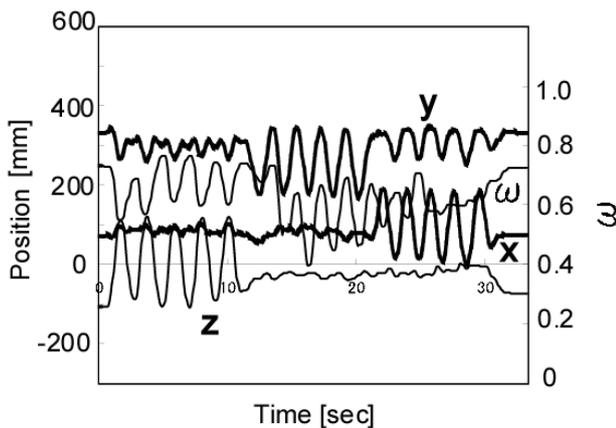


Fig. 13 Overview of master manipulators and an operator



(a) Proposed manipulator



(b) Conventional manipulator

Fig.14 Manipulability of the master manipulator