# Development of an Exoskeleton-type 6-DOF Master Arm for Telexistence

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## Abstract

*We developed the master arm of a telexistence robot for interpersonal communication. To facilitate smooth gestures of the operator, this arm has 6-degree-of-freedom structures to free the operator's elbow. The last degree of the 7-degree-of-freedom slave arm is resolved by placing a small orientation sensor on the operator’s arm. Moreover, this master arm is made light and impedance control is applied in order to grant the operator as much freedom of movement as possible. For this development stage, we compared three control methods, and confirmed that the impedance control method is the most appropriate to this system.*

## 1 Introduction

In order to realize a telexistence [1][2] robot that produces a convincing sense of presence, it is indispensable to capture motion from an operator without restraining his or her free movement, and to correctly display useful power information to the operator at the same time.

The slave arm that we developed this time has 7 DOF, because it aims at communication through gestures [3]. It has the same structure as that of a person, with three DOF at both the shoulder and wrist, and a single DOF at the elbow. For a slave arm with 7 DOF like this one, existing master-slave systems have a master arm used as the operation system, which also has 7 DOF and has an exoskeleton-type structure to capture the operator’s arm’s movement. However, it is difficult to realize free motion of the operator because it tends to restrain the operator's elbow mechanically.

For the Humanoid Robotics Project (HRP) of Japan [4], in order to mitigate an operator's feeling of restraint, a structure that detects the position of the operator's elbow with optical sensors on the 7-DOF exoskeleton-type master arm is adapted, and the master system follows his or her elbow with force feedback function. However, this mechanism introduces a serious time delay to the motion of the slave arm’s elbow. Such a time delay is severely problematic for transferring the operator’s gesture.

To solve this problem, we developed a master arm with 6 DOF that has an exoskeleton-type structure with a small orientation sensor on the operator’s arm, and assessed its performance and efficacy through experiment. We describe here the mechanism design and feasibility evaluation.

## 2 Mechanism design of the master arm

### 2.1 6-DOF arm

From the viewpoint of simplification of function and control, high rigidity, small inertia, and the fact that the power to be applied to the operator’s hand is along at most 6 axes, we designed the master arm to specialize in the power presentation function in these 6 axes, and also made its mechanism 6-DOF.

Since the measurable movement of the master arm that follows the operator's hand has 6 DOF, we decided to use a new lightweight posture sensor composed of two acceleration sensors to measure the final DOF, which is critical to identifying the posture of the operator’s whole arm, including his or her elbow.

Altogether, the mechanism serves as a master system with 7 DOF for measurement of the arm’s posture, and 6 DOF for power presentation. Since the posture sensor is very light compared with mechanical restraints on the operator’s elbow, the sensor enables much freer movement of his or her arm without any undesirable load on it.

Moreover, since the master arm has less than 7 DOF, it achieves power presentation with high rigidity and stability.

### 2.2 Exoskeleton-type 6-DOF Master Arm

As described above, we should leave the motion of the operator as unrestrained as possible in telexistence. Therefore we adapted an exoskeleton-type mechanism for the master arm.

Although the master arm does not necessarily need an exoskeleton-type structure to present forces along 6 axes, it has a mechanism similar to the human body in general, and it always follows human motion. So, we decided to use the structure because we considered that it could be widely adapted for movement of an operator with minimal size requirements, which is an essential characteristic to correspond to a human's various actions in everyday life.

In our system, the number of degrees of freedom in the master arm is less than that of a human arm, so it is impossible for the master arm to follow an operator's whole arm completely, and it introduces the possibility of mutual interference between the human arm and the master arm.

In order to be able to follow a human arm without any interference with only 6 DOF, this master arm must have sufficient clearance for movement of the operator's elbow. The whole schematic of the master arm is shown in Fig. 1. The operator's backbone is located near the center of the circle in the figure. The 190 mm offset between the shoulder joint of the master arm and the elbow joint is the clearance for avoiding interference of the master arm and the operator's elbow, and the offset absorbs the turning radius of the gimbal mechanism at the tip of the arm in Fig. 1.

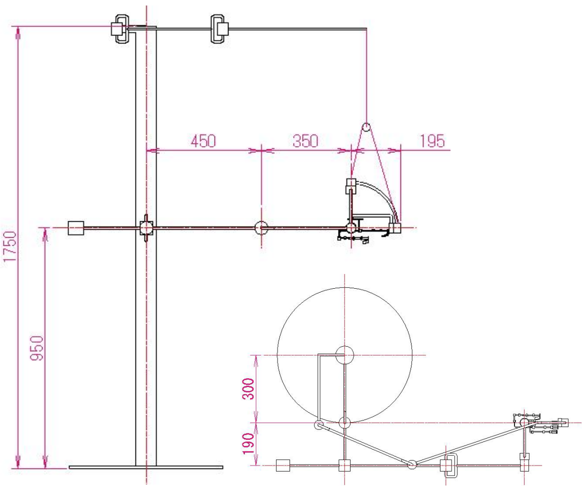


**Fig. 1** The whole schematic of the master arm

### 2.3 Structure of the master arm

The perspective view of the master arm developed this time is shown in Fig. 2.

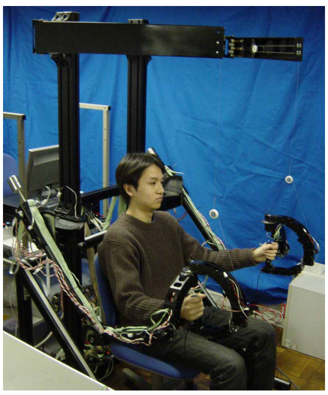

**Fig. 2** The whole view of the master arm

A potentiometer and an encoder are installed in each joint, and the operator's initial posture is computed from the output signals from the potentiometers, and during movement his or her arm’s joint angles and angular velocities are computed from the output signals from the encoders.

The three axes of the joints in the master arm’s wrist cross at one point, as shown in Fig. 3, and a 6-axes force sensor (MINI 4/20, made by BL AUTOTEC) is attached to that point. Output signals from this sensor are used to measure the power that works between the wrist of the master arm and the operator in the direction of the rotating axis, and the torque that works around the axis. The tip of the master arm is currently just a simple grip, but in the near future, we will attach the exoskeleton-type multi-fingered master hand to the tip, and develop a bilateral system including fingers.

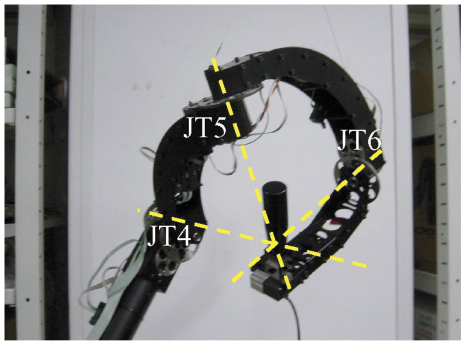


**Fig. 3** The three axes of the wrist cross at one point

The system compensates for gravity by hanging the tip of the master arm with wire, which enables the manipulator to exhibit maximum performance.

Specifications of the master arm are shown in Table 1. The degree values of this table are displayed considering the posture of Fig. 1 as a neutral point.

| | Mobility range of each joint | Output of the motor | Reduction ratio of the gear system |
|---|---|---|---|
| JT1 | -75～60 [deg] | 150 [W] | 125 |
| JT2 | -30～100 [deg] | 150 [W] | 625/6 |
| JT3 | -140～0 [deg] | 36 [W] | 625/6 |
| JT4 | -180～180 [deg] | 12 [W] | 525/4 |
| JT5 | -50～230 [deg] | 12 [W] | 525/4 |
| JT6 | -180～180 [deg] | 12 [W] | 525/4 |

**Table 1** Specifications of the master arm

The gear system of each joint of the master arm is composed of a combination of gears of module 0.3 with grease, as shown in Fig. 4. This ensures high back-drivability, so the arm can be used as a passive master arm.

The mechanism in which an arm tip component is hung with a wire is constituted as shown below. The passive link with two joints is attached above the master arm as shown in Fig. 2. The constant force spring passes inside the link as shown in Fig. 5. Constant tension works on the wire by passing it through the pulley at the tip of the spring. The wire is attached to the tip of the master arm. Since the joints of this link are parallel to the direction of the gravity, the link can follow the master arm smoothly with the wire that circulates through it, while maintaining a horizontal posture.

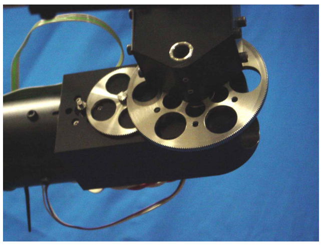

**Fig. 4** The gear system of the joint of the master arm

**Fig. 5** The constant force spring in the link

## 3 The master-slave system with impedance control

### 3.1 Control methods of master-slave system

The previous version of the Telexistence Surrogate Anthropomorphic Robot (TELESAR) [1] adapted unilateral control, but we adapted bilateral control for TELESAR II because of the improvements in technology such as computational power.

Many types of bilateral systems are currently under development, but in this study we control the system based on the impedance control.

The basic principle of the impedance control type master-slave system is to give seemingly equivalent impedance to both master and slave. Furthermore, by minimizing its impedance, the master arm places only a slight load onto the operator's arm, and he or she can perform a wide variety of gestures and other body movement expressions without becoming hindered.

Specifically, control is performed based on the movement equation and the control equations below.

For the master:

$$F_0 = M_d \ddot{X}_m + B_d \dot{X}_m + K_d X_m - F_1 \quad (1)$$

$$F_1 = C_1 \quad (2)$$

For the slave:

$$F_2 = M_d \ddot{X}_s + B_d \dot{X}_s + K_d X_s + F_e \quad (3)$$

$$F_2 = C_2 \quad (4)$$

Here, $(M_d, B_d, K_d)$ mean the target impedance parameters of the master arm and the slave arm, $F_0$ means the operational force to the operator, $F_1$ and $F_2$ mean the inner torque of the master and the slave, $F_e$ means the power that works from the object to the slave arm, $X_m$ and $X_s$ mean the posture vectors of the master and the slave, and $C_1$ and $C_2$ mean the control methods of the master-slave as proposed here.

In the presently adopted Dual Motion Transmission Method, the control methods are as shown below.

$$C_1 = M_d \ddot{X}_s + B_d \dot{X}_s + K_d X_s \quad (5)$$

$$C_2 = M_d \ddot{X}_m + B_d \dot{X}_m + K_d X_m \quad (6)$$

$$F_0 = F_e = M_d\left(\ddot{X}_m - \ddot{X}_s\right) + B_d\left(\dot{X}_m - \dot{X}_s\right) + K_d\left(X_m - X_s\right) \quad (7)$$

Another merit of bilateral impedance concerns operation safety. For contact operations of the slave arm with another person, the operator can feel the power from the person with a high sense of reality, so the potential danger of giving him or her superfluous power can be avoided.

If we control the master-slave system with a Dual Motion Transmission Method [5] that exchanges movement information between the master and the slave, the master's power is equal to the slave's, and exact power presentation can be performed in contact work.

In a state where the slave arm is moved without applying external power, since the master's power and the slave's are not equal, the operator receives power equivalent to the product of target impedance and the posture error. However, making target impedance as small as possible can minimize undesirable load, unlike other control methods.

In order to verify the optimality of this system, we conducted simple comparison experiments with symmetry and force-feedback, which are general control method types.

The symmetry type is a control method in which the master and the slave transmit their posture information to each other, and apply a suitable gain according to the difference of their postures to produce a torque output.

Specifically, control is performed based on the movement equation and the control equations shown below:

For the master:

$$F_0 = M_m \ddot{X}_m + B_m \dot{X}_m + F_1 \quad (8)$$

$$F_1 = K_v\left(\dot{X}_m - \dot{X}_s\right) + K_p\left(X_m - X_s\right) \quad (9)$$

For the slave:

$$F_2 = M_s \ddot{X}_s + B_s \dot{X}_s + F_e \quad (10)$$

$$F_2 = K_v\left(\dot{X}_m - \dot{X}_s\right) + K_p\left(X_m - X_s\right) \quad (11)$$

Here, $(M_m, B_m)$ mean the master arm's impedance parameters, and $(M_s, B_s)$ mean the slave arm's impedance parameters. $K_v$ and $K_p$ are the feedback gains of the velocity and the position.

The power presented to the operator is as shown below.

$$F_0 = M_m \ddot{X}_m + B_m \dot{X}_m + M_s \ddot{X}_s + B_s \dot{X}_s + F_e \quad (12)$$

The force-feedback type is a control method in which the master transmits posture information to the slave, and the slave transmits power information to the master. The master receives the torque command value from the product of the suitable gain and the difference of the master's power and the slave's, and the slave receives the torque command value from the product of the gain and the difference between the master's posture and the slave's.

Specifically, control is performed based on the movement equation and the control equation shown below.

For the master:

$$F_0 = M_m \ddot{X}_m + B_m \dot{X}_m + F_1 \quad (13)$$

$$F_1 = K_f (F_e - F_0) \quad (14)$$

For the slave:

$$F_2 = M_s \ddot{X}_s + B_s \dot{X}_s + F_e \quad (15)$$

$$F_2 = K_v (\dot{X}_m - \dot{X}_s) + K_p (X_m - X_s) \quad (16)$$

Here, $K_f$ is the feedback gain of the force.

The power presented to the operator is as shown below.

$$F_0 = \frac{1}{1+K_f}(M_m \ddot{X}_m + B_m \dot{X}_m) + \frac{K_f}{1+K_f} F_e \quad (17)$$

For each experimental trial, we used the left arm of the master manipulator system as the slave arm because the real slave arm was still under development. In the following text, the word "master" refers to the right arm of the master manipulator system, and the word "slave" refers to its left arm.

In this fundamental experiment, only the yaw-axes of the shoulders of the right and left master arms were moved. Master-slave control was performed such that when the right arm is moved to the left, the left arm also moves to the left, in the same direction.

We investigated the following three concerns in this comparison experiment:

1. When the right arm (virtual master arm) is moved, how well does the slave arm follow?
2. What does the power that the operator gives become in the former experiment?
3. When constant power is applied at the master arm, how strong does the slave arm push the wall?

In all three kinds of comparison experiments, the impedance of the arm in the impedance control type was set as M = 4 [kg], B = 63.2 [kgf/(m/s)], and K = 250 [kgf/m].

First, we describe an experiment that confirmed the ability for the master arm to follow the slave arm. The accuracies of following in the symmetry type, force feedback type and impedance control type are shown in Fig. 6-8.

As indicated in these three graphs, the symmetry type, force feedback type and the impedance control type have almost the same accuracies of following.

Next, we describe the experiment that considered the power that works on the operator. The powers from the master arm that works on the operator in the symmetry type, the force feedback type and the impedance control type are shown in Fig. 9-11.

For the symmetry type, if the operator provides acceleration, a large operational force is needed because of the inertia of both the master arm and the slave arm.

In the force feedback type, because the master is controlled by the power difference between the master and the slave, the power that works on the operator is comparatively close to the value of the slave that does not receive any power.

In the impedance control type, the operational force is relatively small because of the reduction in inertia.

Almost the same power is needed in the force feedback type and the impedance control type. This is considered to be because of the identical structures of the master and the slave in this experimental system.

Finally, we conducted an experiment in which constant force works on the master, and the slave pushes the wall. The results of the measurement of the power in the experiments are shown in Fig. 12-14.

In the symmetry type and the impedance control type, the slave presents almost the same power as the master, but in the force feedback type, the slave pushes the wall with greater power than the power given by the operator to the master. It is potentially very dangerous for a power greater than the operator's to be presented by the slave robot when the slave is interacting with other humans.

The comparison results of the three control methods are summarized in Table 2. As shown here, the characteristics of the impedance control are superior to other two control methods for all three functions.

### 3.2 Slave arm for master-slave system

In the near future, the efficacy of the impedance control will be assessed with an experiment using all 6 joints of the master arm, and the master-slave control with the slave arm that has different dynamic features from the master arm. For this experiment, the 7-DOF robotic slave arm with the same distribution of the degrees of freedom as the human arm and a different mechanical structure from the master arm is being developed at this laboratory. The whole view of the slave arm is shown in Fig. 15.

## 4 Conclusions

This paper described the mechanical design and development of the new exoskeleton-type 6-DOF master arm for telexistence. The validity of the impedance control was confirmed in a fundamental experiment using one joint of the master arm. In the near future, the superior performance of the bilateral impedance control in the master-slave system shall be confirmed through experiment using all 6 joints of the master arm. With this system, the operator will be able to move the slave robot in a remote location very smoothly with a high sense of presence.

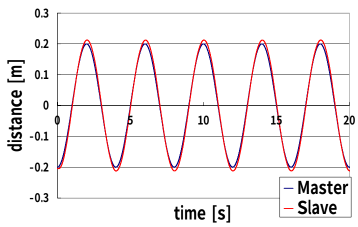


**Fig. 6** Accuracy of following in symmetry type

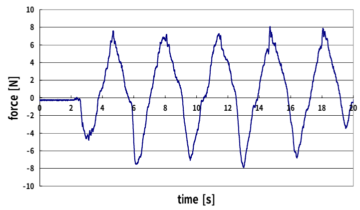


**Fig. 9** Power on the operator in symmetry type

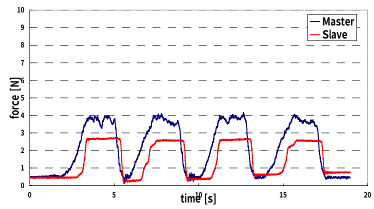


**Fig. 12** Force on the arm in symmetry type

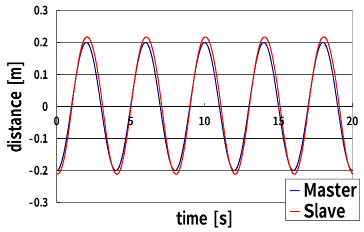


**Fig. 7** Accuracy of following in force feedback type

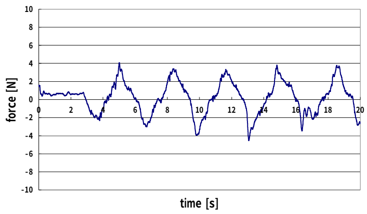


**Fig. 10** Power on the operator in force feedback type

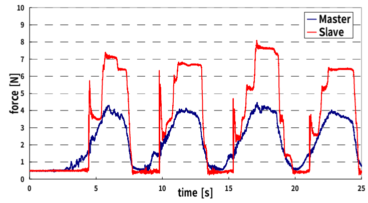


**Fig. 13** Force on the arm in force feedback type

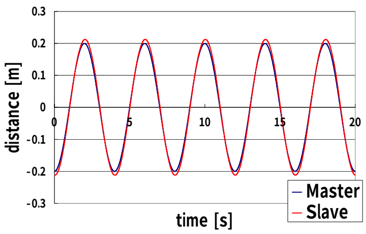


**Fig. 8** Accuracy of following of Impedance control type

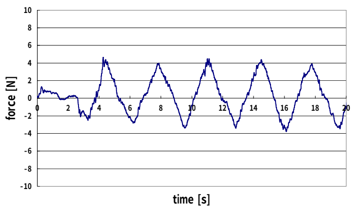


**Fig. 11** Power on the operator in impedance control type

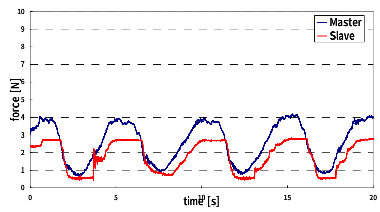


**Fig. 14** Force on the arm in impedance control type

| | Symmetry Type | Force feedback type | Impedance control type |
|---|---|---|---|
| Accuracy of following | Moderate | Moderate | Moderate |
| Operational force | Bad | Good | Good |
| Power presentation | Good | Bad | Good |

**Table 2** Classification of three control methods

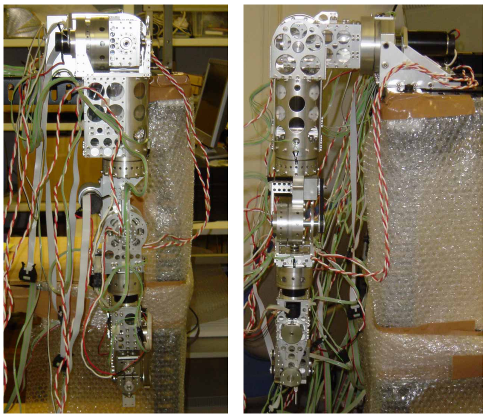

**Fig. 15** The whole view of the slave arm

## 5 Acknowledgments

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