Fifth International Symposium on Magnetic Bearings
Kanazawa, Japan, August 1996

Noncontact Conveyance Using Robot Manipulator and Permanent Magnet

Koichi Oka, Toshiro Higuchi, and Yoichi Shimodaira

Dept. of Precision Machinery Eng., University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113, Japan
tel:+81-3-3812-2111; fax:+81-3-3812-8849; e-mail:oka@intellect.pe.u-tokyo.ac.jp

Abstract: It is known that a magnetic suspension system can be made with a permanent magnet and a linear actuator. The linear actuator is used to control the air gap and makes a suspension system stable. By the application of this suspension mechanism, we can develop the robot manipulator with the function of noncontact conveyance using a permanent magnet. The object carrying capability and system stabilization are combined. Noncontact conveyance may be useful for clean or vacuum environments.

In this paper, the principle of the suspension mechanism and the concept of the noncontact conveyance are explained. An experimental manipulator system which has two degrees of freedom of movement is introduced. This system is theoretically analyzed providing information necessary to suspend the object without contact. Additionally the feasibility of noncontact conveyance was studied. Control parameters are calculated and the control schemes of the states of picking, carrying, and placing are proposed. These results are examined by numerical simulation. Experimental results verify that the noncontact conveyance is actually possible.

1 Introduction

In the semiconductor industry, the development of very fast and large LSI is a main theme. As integration of semiconductor circuits advances, there is an increasing need for better environments and higher precision machines. During circuit fabrication, sources of dust, which can damage an LSI, are eliminated where possible. Since dust is mainly generated from mechanical contact, noncontact oil-free magnetic bearing systems which are used often in place of mechanical bearings are particularly suitable for application in clean rooms and vacuum chambers. In the past, these applications have been proposed [1][2]. But they do not consider mechanical contacts at the handling points. When the end effector picks and places an object, dust is generated.

When a manipulator grasps and manipulates an object which is made of soft materials or includes precision components sensitive external forces, careful handling may be necessary. To deal with difficulties arising from rigid manipulator fingers, control schemes employing force and position feedback have been proposed [3].

The robot manipulator which has the noncontact grasping function may solve these problems. This paper describes the noncontact grasping manipulator with a permanent magnet and a manipulator. The principle of the suspension mechanism, the concept of the noncontact manipulation system, a theoretical analysis, numerical simulation results, and experimental examinations are given.

2 Principle of Suspension

A suspension system with a permanent magnet and linear actuator is proposed as shown in Fig. 1[4]. A ferromagnetic body is suspended by the attractive force from a permanent magnet positioned above. The magnet is driven by an actuator. The direction of levitation is vertical, and the magnet and the object move only in this direction. The equilibrium position determined by a balance between the gravity force and the magnet force.

If the actuator does not actively control the magnet's position, the levitated object will either fall or adhere to the magnet. However servo-control of the actuator can make this system stable. Because there is a smaller attractive

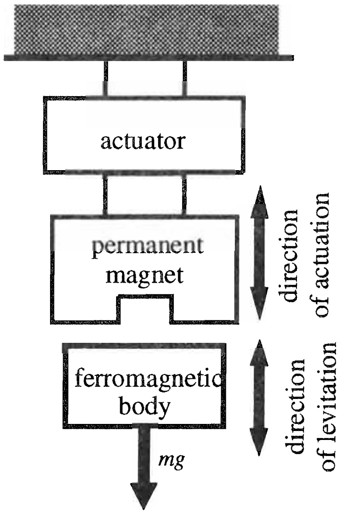

Fig. 1. Outline ofmagnetic suspension system

force for a larger air gap between the permanent magnet and object, the actuator drives the magnet upwards in response to object movement from its equilibrium position towards the magnet. Similarly, the actuator drives the magnet downwards in response to object movement away from the magnet. In this way, the object can be stably suspended without contact.

In comparison to the electrical control method of electromagnetic suspension systems, this system is a mechanical control maglev system.

3 Noncontact Conveyance

The suspension system in Fig. 1 needs a motion control mechanism. Since robot manipulators already possess motion control schemes, it is possible to simply make a noncontact manipulation system through the installation of permanent magnets at the manipulator tip. Manipulator movement not only conveys the object, but stabilizes the suspension system. This manipulation system may solve the problems of dust generation and soft grasping. In addition, as the permanent magnets are used, the system has the merits of no heat generation and no need of current supply cables.

The conceptual illustrations of noncontact manipulation are shown in Fig. 2 and Fig. 3. Fig. 2. shows noncontact pick-and-place motion. A permanent magnet is installed at the tip of the manipulator. First the manipulator brings the tip close to the object. Second, after the tip is positioned close enough, the system controller changes control scheme to suspend the object. Third, the manipulator conveys the object with servo control about the tip position. During conveyance, the manipulator controls both the position and suspension. Last, the object is placed softly on the target location.

Fig. 3 shows a noncontact grasp mechanism for a gravitation-free environment such as outer-space. This magnetic hand can attract the object at a distance and grasp it very softly.

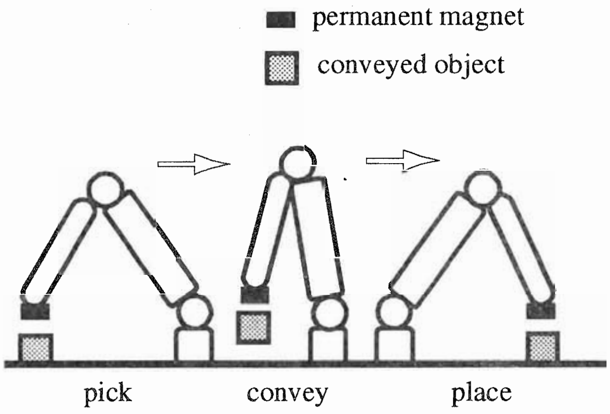

Fig. 2. Noncontact pick and place operation

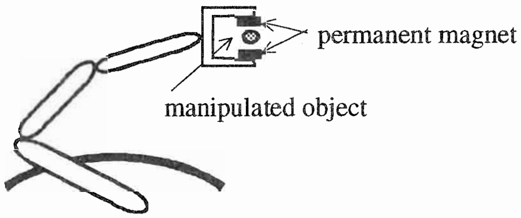

Fig. 3. Noncontact grasping

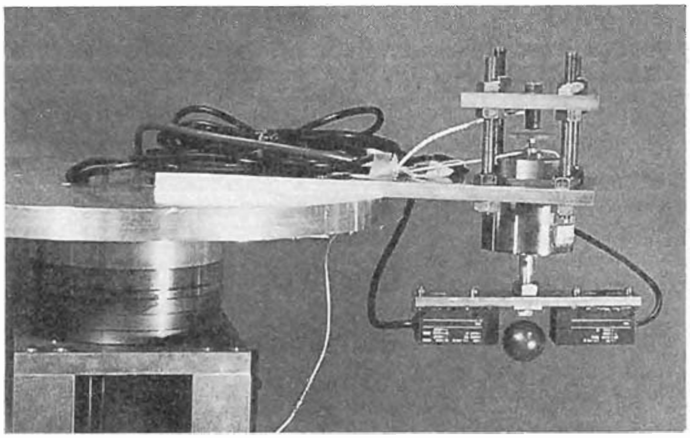

Fig. 4. Photograph of Experimental Setup

4 Experimental System

A basic noncontact manipulation system was constructed. The photograph of the manipulator is shown in Fig. 4 and the structure of the experimental setup is shown in Fig. 5.

The manipulator has two degrees of freedom. The first joint is rotational and turns the table (Joint 1). The second joint is translational and drives the magnet vertically (Joint 2). Joint 1 is actuated by an AC servo motor with a reduction mechanism and Joint 2 is actuated by a voice coil motor (VCM) directly. The angle of Joint 1 is measured by a resolver installed on the motor. The position of Joint 2 is sensed by an eddy current sensor located over the VCM. The sensor resolution is 0.5 μm, and the measurement range is 4 mm. The air gap between the permanent magnet and the suspended object is sensed by a laser gap sensor with resolution of 10 μm and the range of 10 mm. These three signals are converted to the digital signals. The encoder output is counted incrementally and other two analog signals are converted by A/D converters. Based on these digital signals, a DSP controller calculates the appropriate value for the two motors. These values are transmitted to the amplifier and the driver through D/A converters.

The permanent magnet is cylindrical with a 10 mm diameter and 4 mm height. The suspended object is an iron ball with a 19 mm diameter. As the magnet is installed as its flex direction is vertical, horizontal movement of the iron ball is stabilized by the potential force.

The controller has two independent feedback loops: one for Joint 1 and the other for Joint 2. The actuator input of Joint 1 is the reference velocity and is settled by the information of the angle of Joint 1. The amplifier for the VCM is a current amplifier which flows a constant current in proportion to the D/A converter output voltage. As the amplifier response is enough fast and, we assume that the D/A output is equal to the VCM generating force. This propulsive force of Joint 2 is decided based on the information of the position of Joint 2 and the air gap. Cross feedback loops are planned in the future.

5 Analysis and Feasibility Study

For a feasibility study, a theoretical analysis on the system and numerical simulation was performed. Only the vertical directional movement is analyzed. The horizontal movement is stabilized by open loop control.

5.1 Analysis of the Suspension System

The model of the vertical direction of the experimental system is shown in Fig. 6. The system input is the force of the VCM. The outputs are the permanent magnet position and the air gap. Symbols are:

z_0 = position of the iron ball,
z_1 = position of the permanent magnet,
d = air gap,
m_0 = mass of the iron ball,
m_1 = mass of the magnet and the moving part in concert with the magnet,
f_m = attractive force of magnet,
f_a = generation force of the VCM,
g = acceleration of gravity.

The equations of the system are
for the iron ball:

$$m_0 \ddot{z}_0 = f_m - m_0 g \tag{1}$$

for the permanent magnet:

$$m_1 \ddot{z}_1 = f_a - f_m - m_1 g \tag{2}$$

The air gap is represented by

$$d = z_1 - z_0 \tag{3}$$

The attractive force f_m is assumed to be a function of the air gap. By linearization of this function, we obtain

$$f_m = -k_m d \tag{4}$$

where k_m is a constant and $k_m > 0$, and on and after all variables are assumed to be deviations from the equilibrium positions.

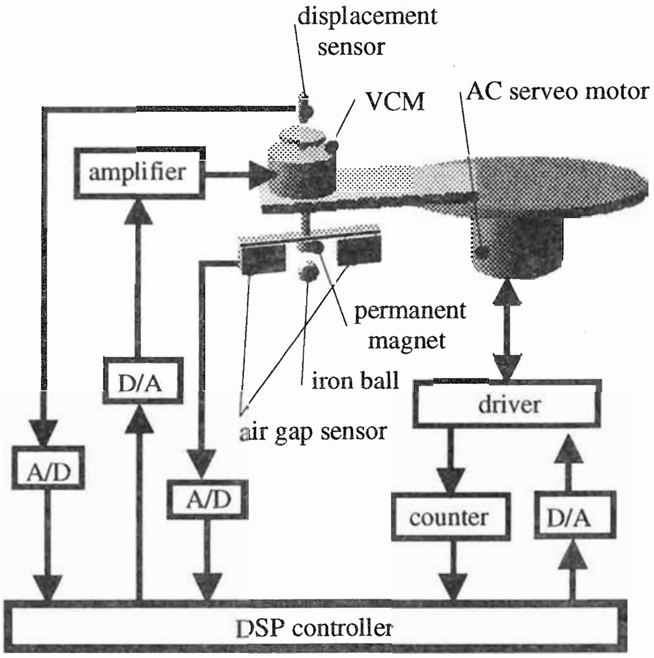

Fig. 5. Construction of Experimental Setup

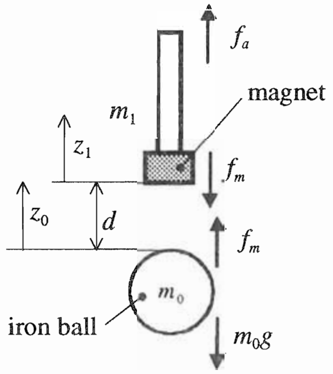

Fig. 6. Model of suspension system

The input of the suspension system in Fig. 6 is the force of the VCM, and the outputs are the magnet position and the air gap. From (1) to (4), the state space model is represented as

$$\dot{x} = Ax + bu \tag{5}$$

$$y = Cx \tag{6}$$

where,

$$x' = (\ z_1 \ \ d \ \ \dot{z}_1 \ \ \dot{d}\ ), \quad u = f_a, \quad y' = (\ z_1 \ \ d\ ),$$

$$A = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{k}{m_1} & 0 & 0 \\ 0 & k(\frac{1}{m_0} + \frac{1}{m_1}) & 0 & 0 \end{pmatrix}, \quad b = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{m_1} \\ \frac{1}{m_1} \end{pmatrix},$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix},$$

and $'$ represents transpose.

The system represented by Eq. (5) and (6) is controllable and observable. We can make the stable suspension system.

Using a PD controller, we obtain the information of all state variables. The control method is represented by

$$u = -(k_{pz} z_1 + k_{pd} d + k_{dz} \dot{z}_1 + k_{dd} \dot{d}) \tag{7}$$

where, k_{pz}, k_{pd}, k_{dz} and k_{dd} are feedback gains.

We examine the conditions of the gains for the stable system. We calculate the conditions by substituting Eq. (7) for Eq. (5) and using the Hurwitz stability criterion. The conditions are

$$k_{pz} < 0 \tag{8}$$

$$k_{dz} < 0 \tag{9}$$

$$k_{pd} > -k_{pz} + \frac{m_0 + m_1}{m_0} k_m \tag{10}$$

$$k_{dd} > -k_{dz} \tag{11}$$

$$m_0 (k_{pz} + k_{pd})(k_{dz} + k_{dd}) > m_1 k_m k_{dd} \tag{12}$$

$$m_0 (k_{dd} + k_{dz})(k_{pz} k_{dd} - k_{pd} k_{dz} + k_m k_{dd}) > -m_1 k_m k_{dz} k_{dd} \tag{13}$$

The conditions of Eq. (8) and (9) are very interesting. On systems which have negative restitution such as in the case with magnetic suspension, system stabilization requires control by a supporting mechanism with negative restitution. This requirement is efficiently used when the manipulator places the object to the floor.

5.2 Control Methods for Noncontact Conveyance

To perform the operation of conveying the object, we must plan its procedure. We divide the operations into 5 procedures.

The manipulator
1) makes its tip to close up to the object,
2) picks the object up,
3) transports the object by the movement of Joint 1,
4) places the object to the floor, and
5) returns to the next object.

Control scheme of the suspension system (Joint 2) is represented by Eq. (7), and that of the turntable (Joint 1) is represented by

$$u_1 = k_1 \theta \tag{14}$$

where θ is the angle error of Joint 1, u_1 is the velocity input of AC servo motor in Fig. 5, and k_1 is the feedback gain. Control methods of the procedure 1) to 5) are describes in the following.

1) The angle of Joint 1 is settled as the magnet locates upward to the object. The magnet position (Joint 2) is controlled by the information of its position. The reference position is that the air gap is a little longer than the equilibrium. The feedback gains k_{pd} and k_{dd} are zero, and the value of k_{pz} and k_{dz} are positive. They are different from Eq. (8) and (9). This feedback control mode is called the position mode.

2) The angle of Joint 1 is still settled as 1). The magnet movement is controlled to make a stable suspension state. The reference position is same as 1). The feedback gains in Eq. (7) are switched to the gains which satisfy the equations from (8) to (13). We calculate the gains by the optimal regulator theory. This feedback control mode is the suspension mode.

3) The reference angle of Joint 1 is changed to the position that the magnet locates on the vertical axis through the placement point of the object. Joint 2 is controlled to maintain the stability. In this stage, as there is no cross feedback loop of Joint 1 and 2, rapid acceleration or braking of Joint 1 may break the stable suspension. To reduce acceleration, we restrict the variation of the velocity input u_1 between one step and next, and give the appropriate feedback gain k_1.

4) After Joint 1 reached to the placement point, the angle is settled. Joint 2 is controlled to place the object to the floor. In practice, while maintaining the suspension control, Joint 2 brings the object close to the target place. After the object has touched the floor, the controller orders Joint 2 to make the magnet to move downward. By this order, the tip is goes up from the equilibrium position inversely.

If the object adhere to the floor, the position of the magnet can be equal to zero. Substituting Eq. (3), (4), and (7), to Eq. (2) and translating the origin, we obtain the equation of the movement of the magnet as

$$\begin{aligned} m_1 \ddot{z}_1 &= fa - fm \\ &= k_{pz} z_r - (k_{dz} + k_{pd} - k_m) z_1 + k_{dz} \dot{z}_r - (k_{dz} + k_{dd}) \dot{z}_1 \end{aligned} \tag{15}$$

where z_r is the reference of z_1.

In Eq. (15), to calculate the balance position, substituting the time deferential terms to zero, we obtain

$$z_1 = \frac{k_{pz}}{k_{pz} + k_{pd} - k_m} z_r \tag{16}$$

From Eq. (8), the numerator of the right hand side of Eq. (16) is negative, and from Eq. (10), the denominator is positive. Thus the variation of the reference z_r causes the movement of z_1 in the opposite direction, and verify the procedure 4).

We assume that z_r is constant to examine the system stability. The terms, in Eq. (15), which effect the system dynamics, is second and forth terms of the right hand side. As the coefficients of these terms are both negative, the stability of the system is verified.

5) After the air gap is enough larger than the equilibrium, the magnet is controlled by its position upward in the movable range. The gains are switched to the position mode. Joint 1 is ordered to turn to the position of the next conveyed object.

The control scheme for Joint 1 is Eq. (14). During the conveying operation, the gain k_1 is constant and the reference angle is varied. This feedback mechanism is a servo system and the stability is verified.

On the other hand, Joint 2 feedback gains represented by Eq. (7) are not constant. When the procedure changes from 1) to 2) or from 4) to 5), the gains are switched from the position mode to the suspension mode or are switched in inverse. In this case, the stability of the system is not verified. The numerical analysis is needed.

5.3 Numerical Simulation

To verify the stability in switching the gains and the realization of the placing operation by the control method of the procedure 4), numerical simulations on the model is made. The executed simulation is the procedure 1), 2), and 4). The 3) and 5) which actuate Joint 1 are omitted. The simulation of the procedure 3) is important to verify to keep stability against the effect of the actuation of Joint 1. However, we can not simulate, because we do not estimate the horizontal direction element of the attractive force of the magnet.

The attractive force of the magnet is approximated as

$$f_m = \frac{k}{d^2} \tag{17}$$

where k is constant. The sensed values which is the gap and the magnet position are quantized to 1 μm. The sampling period is 0.1 ms. The approximated differential is used for the velocity of the controller.

Numerical simulation results are shown in Fig. 7. Simulations begin at the time when the controller changes from the procedure 1) to 2). The initial position of the magnet is 2 mm above the equilibrium. At 1 second, the placing motion starts. The gains of the simulations are calculated by an optimal regulator. The floor position is zero, and the upward direction is positive. The air gap of the equilibrium position is assumed to be 8 mm. The ball position is set to be non-negative value.

The figure shows that the suspension system can pick the iron ball without a contact and the system keeps stability. In placing motion, first the magnet moves upward slightly and the ball begins going down. After the iron ball touches the floor, the magnet moves upward. Before the ball touches the floor, the movement of the ball is almost equal to the input signal. After the touch, the magnet moves up slowly according to Eq. (16).

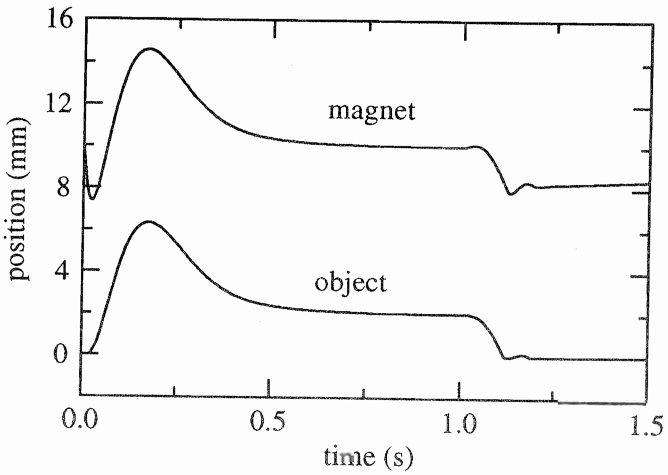

Fig. 7 Simulation result

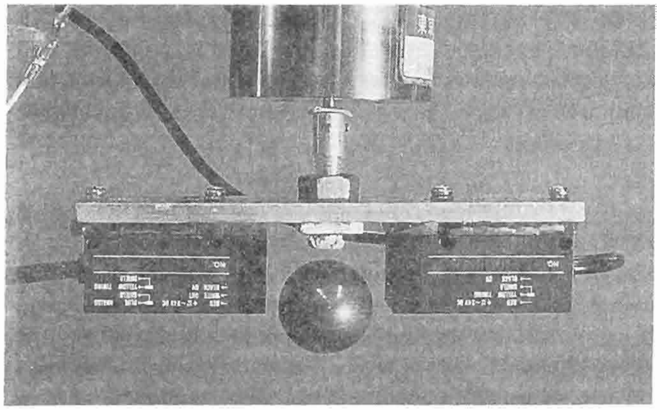

Fig. 8 Phtograph during suspension

6 Experiments

A suspension experiment was carried out. A photograph during suspension is shown in Fig. 8. As can be seen, success for noncontact suspension was achieved.

The result of the noncontact conveyance operation is shown in Fig. 9 and Fig. 10. In Fig 9, the procedures of 1) to 4) are recorded and they are indicated upper of the figure. The air gap and the magnet displacement, and the velocity of Joint 1 are recorded. In Fig. 10, the procedures of 2) and 4) are shown. The gap, the magnet displacement, and the input of the suspension system (the input of the VCM amplifier) are recorded. The magnet displacement and air gap are sensor outputs, not absolute values, the velocity is the output of motor driver unit, and the input is the output of the controller.

As seen in Fig. 9, after Joint 1 starts rotating, the magnet position vibrates. The reasons is the horizontal force which is caused by the acceleration of Joint 1. The force makes the air gap to be varied. Regardless, it is seen that the air gap is almost fixed.

In Fig. 10, we can see the vibration and the input overload at picking up motion. At placing, a slight bound is seen in the magnet movement. This bound is also seen in simulation and may be the effect that the velocity of the ball varies rapidly. These experimental results, however, verify success of the noncontact conveyance operation.

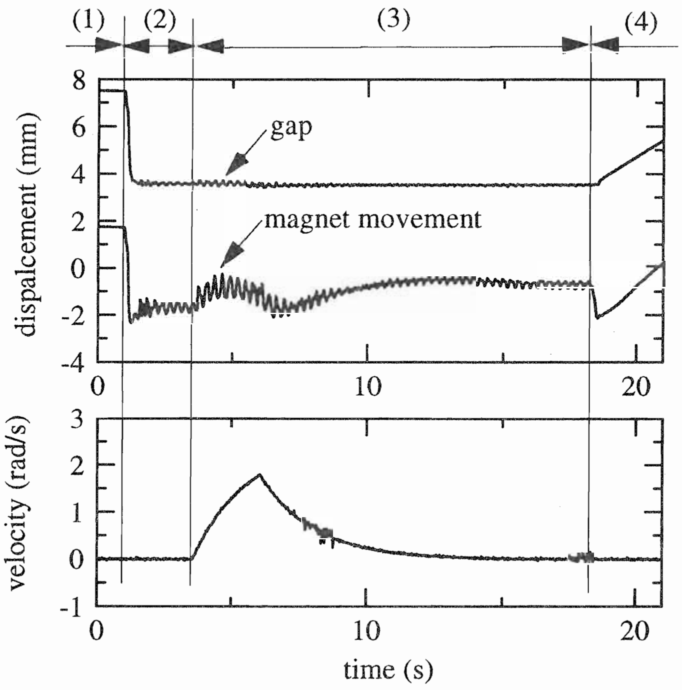

Fig. 9 Experimental result (procedure 1)-4))

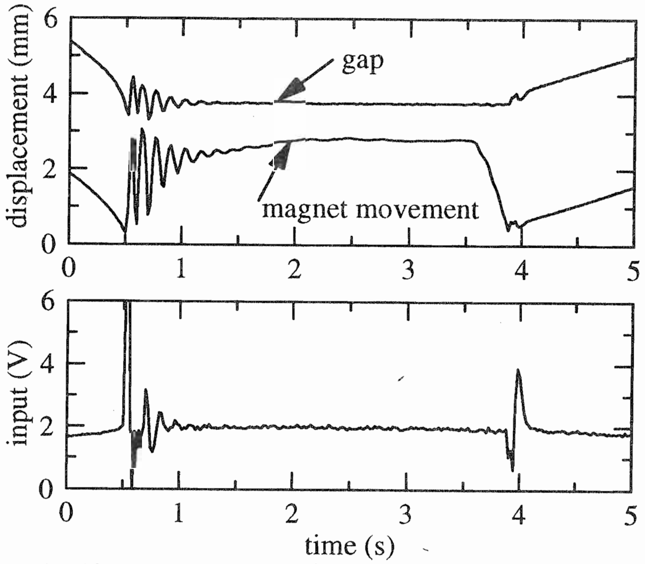

Fig. 10 Experimental result (prodedure 2) and 4))

7 Conclusion and Further Study

Noncontact conveyance operation with a permanent magnet and a robot manipulator was proposed. The experimental system was introduced and the theoretical analysis verified. The noncontact conveyance operation was proposed, and was verified theoretically and by simulations. Experimental examinations were carried out and noncontact conveyance was succeeded.

The robot manipulator shown in Fig. 4 has a structure which is easy applicable to the conveying function. The vertical and direct drive of the magnet have advantage. As the further study, we made a robot manipulator shown in Fig. 11 to confirm that usual manipulators are able to convey the object without mechanical contacts. The noncontact conveyance using the manipulator will be examined.

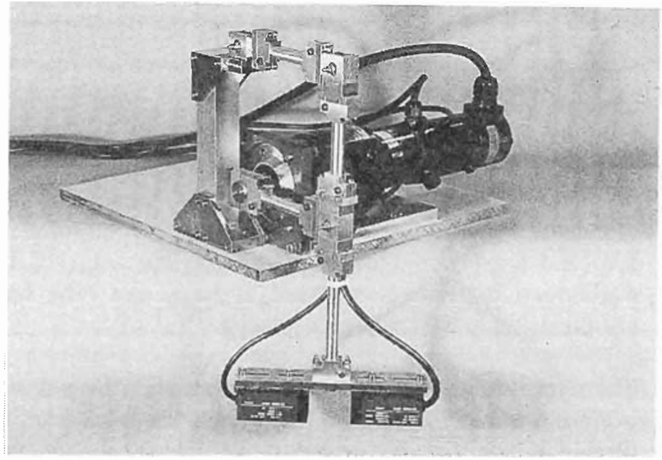

Fig. 11 Manipulator with reduction mechanism and link

References

[1] M. Ota, S. Ando and H. Inoue, "Mag-lev Semiconductor Wafer Transporter for Ultra-high-vacuum Environment", *2nd International Symposium on Magnetic Bearings*, pp.109-112, 1990.

[2] T. Higuchi, A. Horikoshi and T. Komori, "Development of an Actuator for Super Clean Rooms and Ultra High Vacua", *2nd International Symposium on Magnetic Bearings*, pp.115-122, 1990.

[3] e.g. M. H. Raibert and J. J. Craig, "Hybrid Position/ Force Control of Manipulators," *Trans. ASME, J. of DSMC*, 1981.

[4] K. Oka and T. Higuchi, "Magnetic Levitation System by Reluctance Control," *Int. J. of Applied Electromagnetics in Material*, Elsevier, 1994.