DESIGN OF MAGNETICALLY LEVITATED MICRO OPERATION HANDS

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SUMMARY

Application of magnetic levitation technology to mechatronics has a possibility of compact design of machine, since no transmission mechanism is required. Furthermore, because of non-friction, force control is easy to implement and high accuracy is expected in position control. These features are also effective in robotics. In our research, mechanism and control of micro operation hands are investigated. The hand consists of two finger rods each of which has three degrees of freedom and is controlled by an independent finger subsystem. To realize this finger subsystem two models are considered: a hybrid (magnetic and mechanical) suspension model and a full levitation model. A novel magnetic actuator composed of a permanent magnet and an air-core coil is used for actuation and suspension in the models. The basic characteristics of the actuator is analyzed and it is shown that it has a good property for motion control. Also it is shown that the actuator works as a useful passive suspension component which is used in the full levitation model. Finally, results of a task of micro drawing using the hybrid model are presented.

INTRODUCTION

Research on applications of magnetic levitation technology to manufacturing areas are conducted recently. One feature of the technology used in this area is the manipulation capability of objects in vacuum environments such as clean rooms in semiconductor industry[1,2]. Another feature is the low friction and force control capability[3]. For such applications in robotics a robotic hand with magnetic bearing, a haptic interface[4], that is, a magnetically levitated joystick, by which the operator can sense force feedback, etc. are developed. Recently, research on devices for micro operation in a biological / medical area and a micro machine area are a center of attraction. In such areas, devices by which operators can do dexterous operations for biological cells, a human body or mechanical parts are required[5,6]. Force control is considered to be effective to these dexterous operations even in the micro world, where tasks of assembly and machining such as cutting objects are necessary. Up to this time, a ball screw mechanism driven by electrical motors or a link mechanism driven by piezoelastic actuators are developed. Force control is difficult to implement using these mechanisms. However magnetic suspension type devices have not been developed yet for these tasks.

In our research, mechanisms and controls of micro operation hands are investigated. The hand consists of two finger rods each of which has three degrees of freedom and is controlled by an independent finger subsystem. Fig.1 shows a concept of micro operation by a two-finger micro operation hand which is attached to a macro robot. The macro robot is used to position the micro operation hand roughly in a large work space. Therefore, the workspace of the micro operation hand considered is more than the volume of 10_10_10 mm, since the size of micro machine is defined as this size. Operations considered are machining and assembly. The two fingers are used as a gripper for the assembly application. If a micro tool, such as a drill or a knife, is attached, drilling or cutting processes can be done. The operator observes the operations through a microscope and performs a task using an interface such as a joystick. To realize this finger subsystem two models are considered. (1) A hybrid (magnetic and mechanical) suspension model and (2) a full levitation model are considered. The model (1) uses a link mechanism with mechanical bearings to constrain the finger motion. Each degree of freedom is driven directly by a magnetic actuator. A lever mechanism was tested to realize the model (1). The model (2) can be used for fine operations in the environment where mechanical suspension is not suitable. Passive suspension components are investigated to simplify the control and the preliminary test was conducted.

To develop these models, a novel but simple magnetic actuator composed of a permanent magnet and a air-core coil is proposed for actuation and suspension. A magnetic field inside a coil is almost constant near the center of the coil and, if the pole of the permanent magnet is there, an actuator with linear characteristics suitable for motion control is obtained. Another feature of the actuator is that a magnetic force acts outward of the coil on a pole of the magnet and it can be used as a spring at the position away from the center. Then the design of two models are presented and illustrated how to use the actuators, although current states of prototype development are in different phase in each model.

Finally the results of a task of micro drawing are presented using a prototype of the lever mechanism, where a position control is conducted in the direction tangential to the contact surface and a force control in the direction normal to the surface. The position controller uses a disturbance observer which is robust against model errors and disturbances, and its effectiveness is shown experimentally.

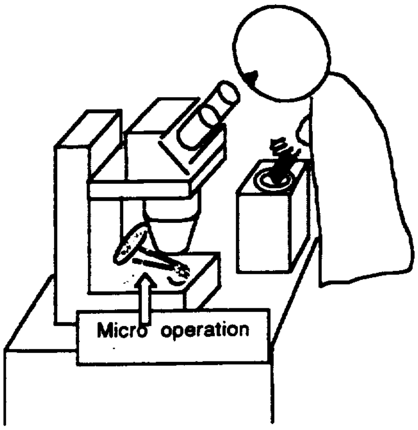
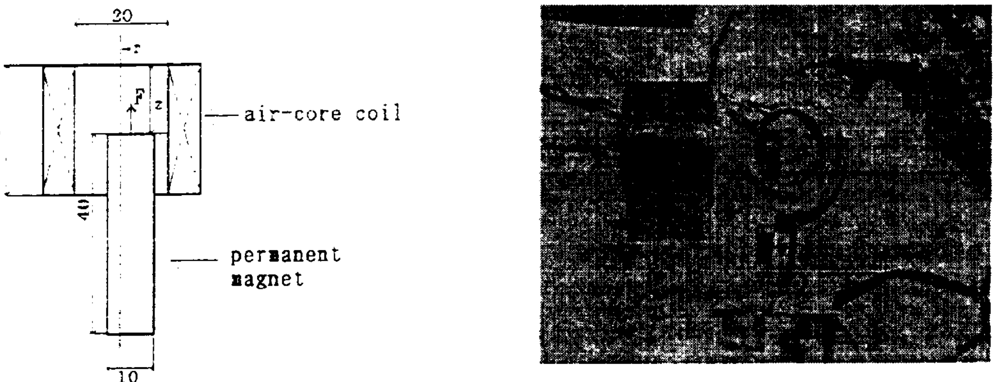


Fig.1 Concept of a micro operation hand

MAGNETIC ACTUATOR

The actuator proposed for micro operation hands consists of an air-core coil and a permanent magnet as shown in Fig.2. The permanent magnet is attached to the finger rod and the coil is fixed in the base frame. The actuation is done in the axial direction of the coil. The inner diameter of the coil is large enough for the pole of the permanent magnet to move around in the volume corresponding to the workspace. Apparently, there is a magnetic force in the radial direction at the place away from the axis. However if the radial force is small compared with the axial force, the problem is not significant for the control of the finger rod. The axial force is almost constant at the position near the center of the coil and proportional to the coil current, and this is a property suitable for motion control.



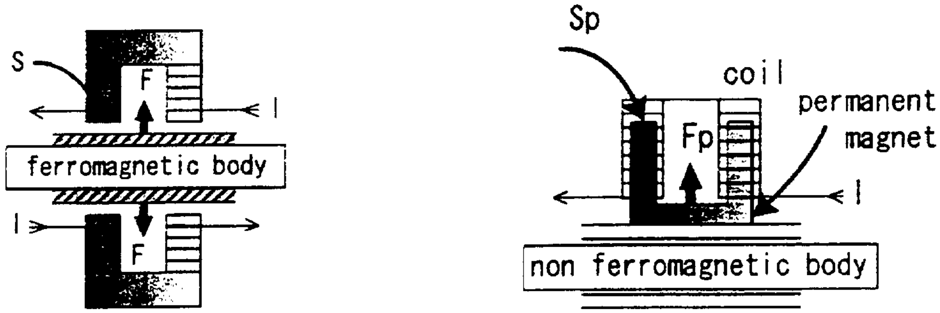
(a) structure

(b)photograph

Fig.2 Magnetic actuator

Driving Force

A conventional type actuator is multiple electromagnets as used in magnetic bearing. Driving force of our actuator is compared with that of the conventional type actuator under the same condition with respect to the size and current of the coil. Magnitudes of driving force are estimated using the models in Fig.3, where (a) is a conventional type and (b) is ours. Assume that the conventional type contains an iron



(a) conventional type

(b) proposed type

Fig.3 Comparison of two types of actuator core inside a coil, while our type contains a permanent magnet. Let S[m^2], I [A] and n [/m] be the cross-sectional area, the electrical current and the number of windings per unit length of the coil respectively. Then the magnetic field H is given by

$$H = n\,I \tag{1}$$

Let us estimate maximum forces for both types. Suppose the gap is very small for the conventional type. Then the magnetic force F is given by

$$F = 2_{\mu}H^{2}S \tag{2}$$

where _ is a magnetic permeability of the object. Consider our type. Let the area of the cross-section of the permanent magnet be S_p. Both poles of the magnet are assumed to be inside the coil . Then the magnetic force F_p is

$$F_p = 2HS_pM \tag{3}$$

where M is the magnetization of the permanent magnet used.

Let us compare F and F_p. Typical values of the parameters are μ=0.002[NA^{-2}] for an iron and M=0.8[T] for a rare earth magnet.

$$S_p < S \tag{4}$$

But our type can generate a larger force than the conventional type for small H, since $M > \mu H$. For large H, the magnetization is saturated. It depends on the material and the saturated magnetization is about 0.8[T] at H=105[A/m] for silicon steel. But the linear region of the B-H curve shows M<0.6[T]. If the gap between the object and the electromagnetic pole is small enough for the conventional type,

$$F \fallingdotseq F_p \qquad \text{for a small gap.} \tag{5}$$

However, the magnetic force decreases rapidly as the gap increases. Therefore our type is significantly stronger as a whole.

Linear Characteristics

Consider a multi-layer cylindrically wound coil. Let r and z be the radial and axial distances from the center of the coil as shown in Fig.2. Let $H_r(r, z)$ and $H_z\,(r, z)$ be radial and axial components of the magnetic field $\boldsymbol{H}$ at the position (r, z) as shown in Fig.4. Magnetic intensity on the axis $H_z\,(0, z)$ is given by

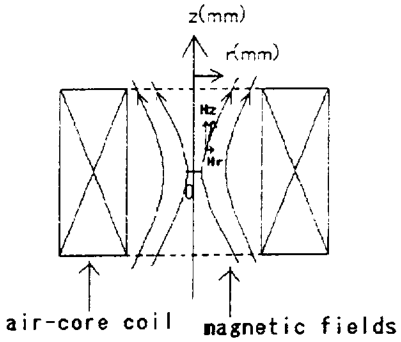


Fig.4 Magnetic field inside the air-core coil

$$H_z(0,z)=\frac{nI}{2(a_2-a_1)}\left\{(b+z)\ln\frac{a_2+\sqrt{a_2^2+(b+z)^2}}{a_1+\sqrt{a_1^2+(b+z)^2}}+(b-z)\ln\frac{a_2+\sqrt{a_2^2+(b-z)^2}}{a_1+\sqrt{a_1^2+(b-z)^2}}\right\} \tag{6}$$

where
a_1: an inner diameter of the coil,
a_2: an outer diameter,
b: half length of the coil,
n: the number of windings per unit length,
I: coil current.

The theory was compared with the measurement. Magnetization of the permanent magnet and coil current were assumed to be 0.8[T] and 0.2[A] respectively. The results are shown in Fig.5 and 6. Theory and measurement give similar results but the z-values which gives a maximum magnetic force are different. The reason for this is that the effect of the pole of the other side of the permanent magnet is not taken into consideration in the theory.

The magnetic field at the position away from the axis can be theoretically calculated using the magnetic equations inside the coil.

$$\text{Div}\,\boldsymbol{H}=0 \tag{7}$$

$$\text{Curl}\,\boldsymbol{H}=0 \tag{8}$$

From Eq.(8), ***H*** is a potential. H_r and H_z are obtained from Eq.(7) by using a potential function approximated up to the second order with respect to r and z in its Taylor series expansion.

$$H_z(r,z)=H_z(0,z)-\frac{1}{4}r^2\left(\frac{\partial^2 H_z}{\partial z^2}\right)(0,z) \tag{9}$$

$$H_r(r,z)=-\frac{1}{2}r\left(\frac{\partial H_z}{\partial z}\right)(0,z) \tag{10}$$

Eq.(10) shows that the radial component of H_r is small near the center of the coil and the actuator can be used to drive the permanent magnet in the direction of z.

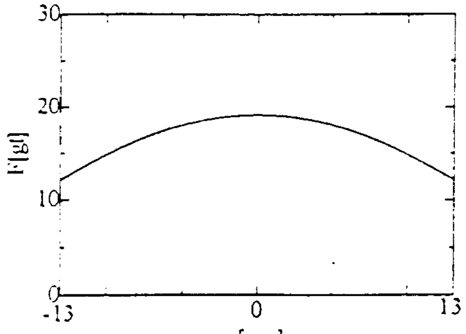


Fig.5 H_z on the z-axis (theory)

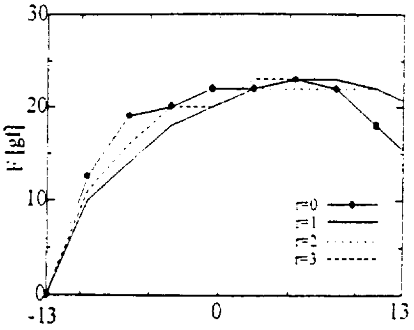


Fig.6 H_z on and off the z-axis (experiment)

Passive Magnetic Spring

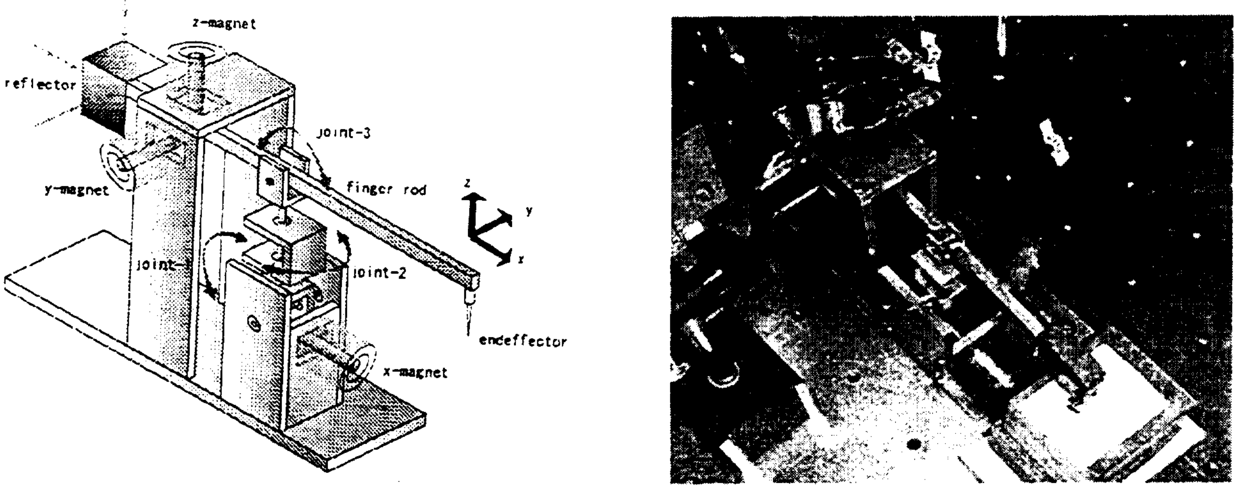
The distribution of magnetic field along the axis shows that the actuator works as a spring without control if a positive magnetic pole is placed at z>0 inside the coil. Therefore, if a positive magnetic pole is placed at z>0 , the magnetic pole is levitated at the position where the magnetic and gravitational forces balance. Although it contacts with the internal surface of the coil, the radial force is not significant so that it can be used as a passive suspension component. This magnetic spring is effective to reduce the degree of freedom actively controlled.

DESIGN OF MICRO OPERATION HANDS

We propose two models for one finger subsystem of a micro operation hand; (1) a hybrid (magnetic and mechanical) suspension model and (2) a full levitation model.

Hybrid Model

A prototype with a lever mechanism was developed and tested for micro drawing . Its structure and photograph are shown in Fig.7. A finger is constrained with a three DOF link mechanism and three motions of rotations around joints 1, 2 and 3 are allowed. Rotations around these joints generate approximate straight line motions of the finger tip in x, y and z directions due to the relatively longer lever compared with the size of the workspace. Three DOF positions are measured at the opposite side of the finger with laser displacement sensors. Magnetic actuators are placed apart by enough distances not to interfere at this side. This mechanism has the following features:



(1)structure (2)photograph

Fig.7 Prototype of the hybrid model (lever mechanism)

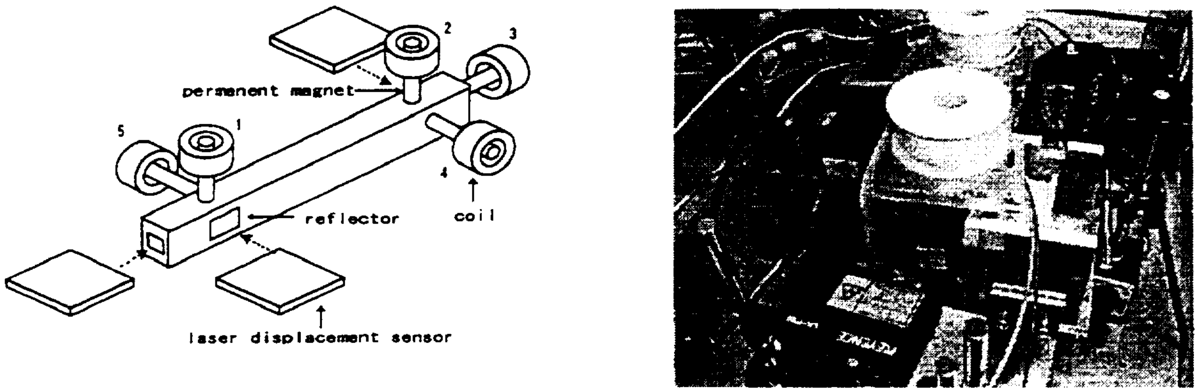
(1) (Near) line motions of the finger tip are possible using a MAGLEV technique.
(2) Gravity is decoupled by using counter balances for various postures of the micro hand.
(3) Effects of the joint frictions is minimized for fine motions.
(4) The mechanism is rigid in a constrained DOF motion
(5) Compact and light weighted design is possible. Specifications of the prototype are as follows:

[link mechanism]

size:	L320 x H110 x W175 mm
weight:	1 kg
workspace:	10 × 10 × 10 mm
[sensor]	
type:	Keyence LK-2000
range of measurement:	±5 mm
resolution:	1 μm
response time:	512μs
[coil]	
size:	φ20 mm(internal diameter)x26 mm(length)
windings:	550 turns with wire ofφ0.5 mm
force:	120 gf /A

Full Levitation Model

A full levitation model has diverse potential applications because of the simplicity of the mechanism. Especially a compact design of hands might be possible in the applications which do not require large operational forces. At the beginning, the feasibility was tested using the model illustrated in Fig.8(a) and experimental apparatus shown in Fig.8(b). The actuators 1 and 2 are used as passive springs and the upward magnetic forces balance with the gravity force. Other actuators 3, 4 and 5 are actively controlled using the corresponding laser displacement sensors. Fig.8 shows the experimental apparatus.



(a) structure

(b) experimental apparatus

Fig. 8 Full levitation model for feasibility test

The sensors are the same as the ones used in the hybrid models but more powerful coils are used for actuators. The specifications of the coil are as follows:

size:	φ 25 mm(internal diameter) × 26 mm(length)
windings:	1000 turns with wire of φ 0.7 mm
force:	250 gf / A

An aluminum regular prism of 18x18x260 mm with a weight of 500 gf including permanent magnets was easily levitated using a simple PID control for the actuators 3, 4 and 5.

TASK OF MICRO DRAWING USING A HYBRID MODEL

The results of a task of micro drawing are presented in this section, where the prototype of the hybrid model is used and a pen is attached to the finger tip to draw figures on a paper parallel to the x-y plane, where x, y and z axes are defined in Fig.7. A position control is conducted in the direction tangential to the contact surface, that is x and y directions in this case. At the same time, a force control is conducted in the direction normal to the surface, that is z direction. The position controller is designed using a disturbance observer which is robust against model errors and disturbances, and its effectiveness is evaluated experimentally.

Control System

A position and force control is used for the contact motion control. However the force control is simply an open loop control since the coil current is proportional to the normal force applied to an object, while the position control suffers from disturbances such as friction. It also suffers from modeling errors when a linear controller like PID is used. Recently, a disturbance observer is known for its robustness against disturbances and modeling errors, and it is implemented in various motion controls.

For these reasons, we applied a disturbance observer to the position control. Assume that the x, y and z motions of the end effector are decoupled. Since the mechanical time constant is longer than the electrical constant, the end effector motion in a direction is formulated as follows:

$$\frac{dv}{dt} = \frac{p'q'}{R'}u - f_{dis} \tag{11}$$

where u is a control, f_{dis} is a disturbance, and p', q' and R' are nominal values of parameters p, q and R:

p: amplification rate of the amplifier
q: force constant of the actuator
R: resistance of the coil

The principle of disturbance observers [8] is stated as follows: "If $\dot{v}$ and u are known values, we can estimate the disturbance from Eq.(11). Then, by adding the corresponding value to u we can cancel the disturbance." In our system, velocity $\dot{v}$ is not measured thus $\dot{v}$ has to be estimated from the displacement, say x, where

$$v = \dot{x} \tag{12}$$

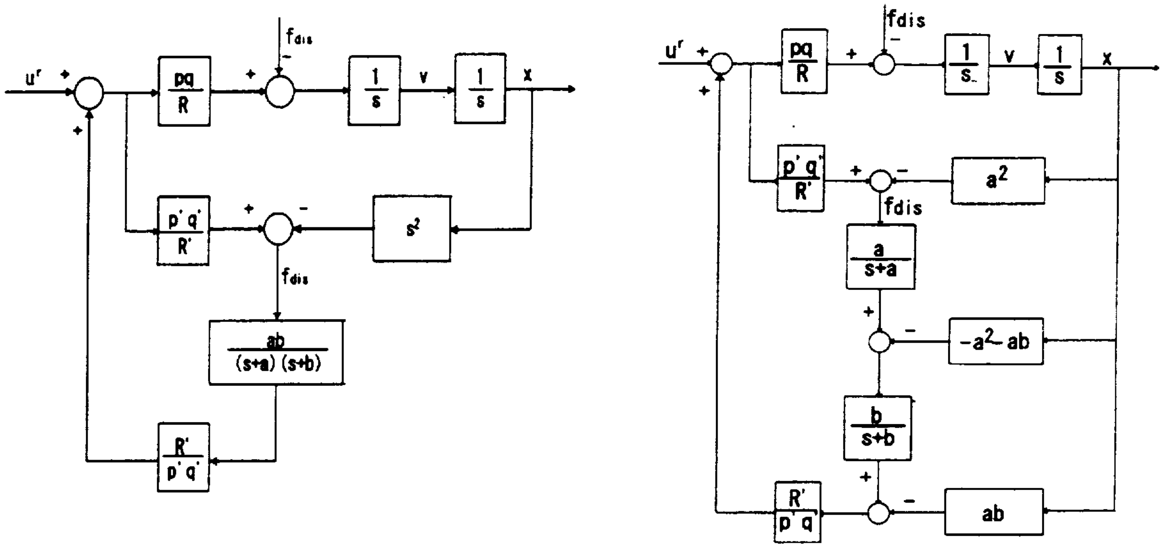
Fig.9(a) describes this principle in the form of block diagram, where a low pass filter is added to reject noises.

$$\frac{ab}{(s+a)(s+b)} \tag{13}$$

However, Fig.9(a) is not desirable since derivative operations are included. But Fig.9(a) can be converted to the diagram as shown in Fig.9(b) which contains no derivative operation. The reference u^r of the control can be determined by PID control law.

$$u^r = K_p(x_d-x)+K_i\int(x_d-x)dt+K_d(v_d-v)$$

where K_p, K_i and K_d are PID gains, and x_d and v_d are desired values of x and v.



(a) a form including derivative operations

(b) a form without derivative operations

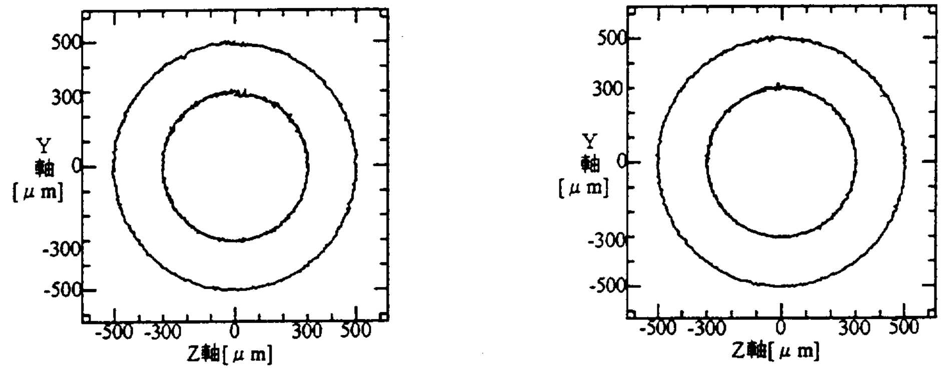
Fig. 9 Disturbance observer for position control

Experiments

In the experiments, a pen and a counter balance were attached to the tip of the finger rod. The total weight of the finger rod is 120 [gf] including the weights of permanent magnets, the counter balance and the pencil. Using this experimental setup, the effectiveness of the disturbance observer was experimentally investigated by drawing small circles in the air in case of free motion and on a paper placed in case of contact motion. In both cases, the circles are parallel to the x-y plane. In the free motion, x, y and z are position controlled. In contact motion, x and y are position controlled, and the force in z-direction is open-controlled. The discrete-time form of the controller described above was derived by approximation and implemented on a computer. Sampling time of 1[ms] was used. This value is related with the resolution of the measurement and the derivative operation of the PID control law.

Free Motion

Fig. 10 shows the trajectories formed from the data of the laser displacement sensor outputs where references are circles with radii of 300 and 500 [_m] and the operational time t=13.6[s]. In this figure, (a) results in case of without disturbance observer and (b) with disturbance observer are shown. Comparing these figures significant differences can not be observed. On the other hand , Fig. 11 shows the results with t=0.72 [s]. In this case, the non-linearity of the actuator and the dynamics can not be cancelled with the integral operation of PID. So the result without disturbance observer deviates from the reference circle.



(a) without disturbance observer

(b) with disturbance observer

Fig.10 Experimental results in free motion (t=13.6)

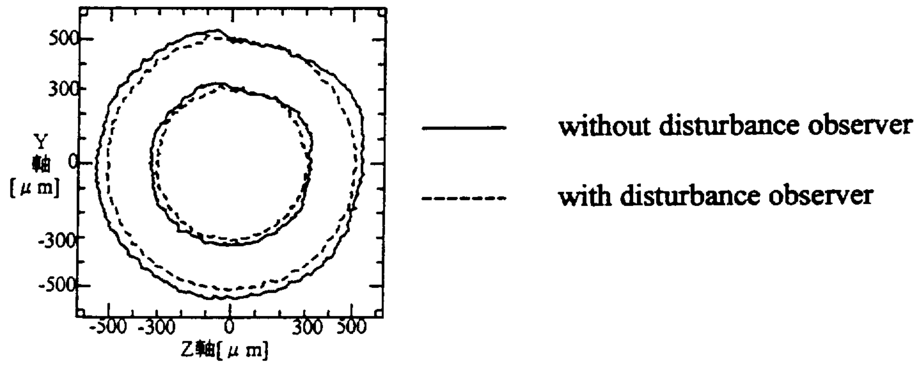
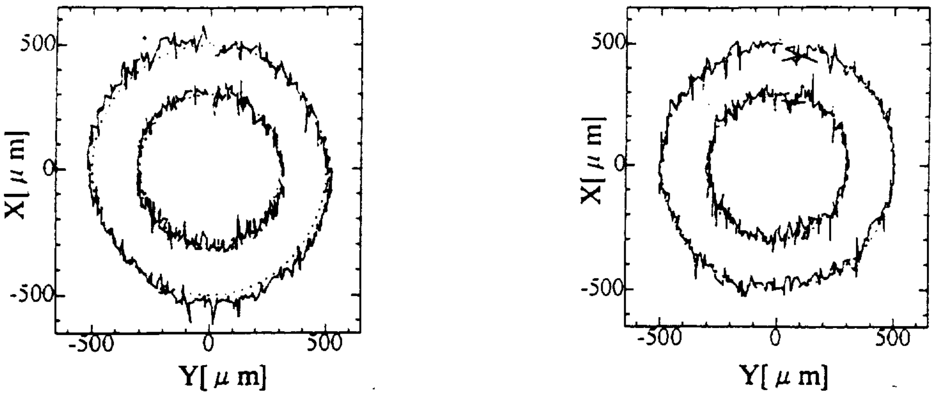


Fig.11 Experimental results in free motion (t=0.72)

Contact Motion

Fig.12 shows the results in contact motion where references are circles of radii 300 and 500 [μm] and t= 13.6 [s]. Force enough to draw circles on the paper was applied to the z-direction. The applied force was 24 [gf]. (a) is the results without disturbance observer and (b) is the ones with disturbance observer.



(a) without disturbance observer (b) with disturbance observer

Fig.12 Experimental results in contact motion (t= 13.6)

Both results show the stick-slip motions of the endeffector. However (a) shows smaller stick-slip motions._This tendency is obvious from the graph y(t) of the straight line contact motion with applied force of 100[gf] as shown in Fig. 13. Moreover, Fig.12 shows that (a) deviates from the reference circle but (b) is on the reference circles in average.

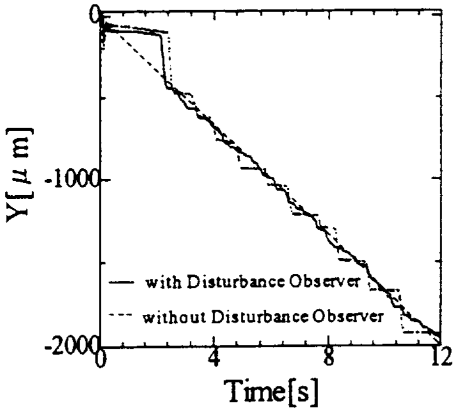


Fig.13 y(t) in the experiments of straight line contact motion

CONCLUSIONS

This paper proposed a micro operation hand. Finger subsystems with a hybrid model and full levitation model were presented. Our idea is a novel actuator which consists of a permanent magnet and an air-core coil to realize a magnetically levitated micro operation hand. Characteristics of the actuator was analyzed and it was shown that it has a linear characteristics suitable for the control. It can also be used as a passive suspension component without control. The effectiveness of the actuator was verified by making a prototype and a feasibility test model. Finally the hybrid model was applied to a task of micro drawing and the performance was evaluated experimentally. Especially, the effectiveness of a disturbance observer was tested, where disturbances are friction in a contact motion and some nonlinear terms in the equation of motion of the mechanism and the actuator characteristics. The experimental results show that the disturbance observer is effective for disturbance rejection.

The applied task was micro drawing in this paper but our goal is to apply a micro operation hand to various tasks. A two-finger micro operation hand each finger of which is constrained with a parallel link mechanism is also being made for assembly and machining of micro products. It will be presented in the near future. Also we are going to develop a prototype of the full levitation model with a compact size in future. We are considering that this model is effective to biological or medical applications.

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