Object Conveyance System "Magic Carpet" Consisting of 64 Linear Actuators - Object Position Feedback Control with Object Position Estimation -

Hichirousai Oyobe and Yoichi Hori

Department of Electrical Engineering
University of Tokyo
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, JAPAN
oyobe@hori.t.u-tokyo.ac.jp, hori@hori.t.u-tokyo.ac.jp
http://www.hori.t.u-tokyo.ac.jp/997/oyobe/index.html, www.hori.t.u-tokyo.ac.jp/staff/hori/index-j.html

Abstract— **A novel object transfer system named "Magic Carpet" composed of linear actuator array and driven by autonomous decentralized type control algorithm is proposed. An object is manipulated by a large number of contact points with many actuators, which differs from conventional systems like belt conveyor. In this paper, the control algorithm for such "distributed manipulation" is proposed.**

Due to recent development of micromachine technology, distributed manipulation becomes more important. This system has a big advantage in its fault tolerance because it has a lot of actuators with poor performance to move a large heavy object. However, it has a serious wiring problem to be solved and homogeneous structure should be introduced because of a large number actuators.

To solve these problems, "combined control of central /autonomous decentralized algorithms" is proposed and effectiveness of proposed object position control algorithm based on feedback is confirmed by computer simulation. To realize this feedback, the object position estimation algorithm is too proposed.

I. Introduction

There are various kinds of scheme to move objects. Object transfer by belt conveyor and robot manipulator is firstly considered. Distributed manipulation effects an object through a large number of contact points and object transfer by this distributed manipulation scheme is attempted in various field [1]. This manipulation is very similar to transfer scheme by lifting someone into the air by many persons and also has the following benefits:

1. **fault-tolerant**
2. **large heavy object transfer by many small poor actuators**

This concept means not to get high performance by only one actuator but to get high performance by small simple many actuator cooperation. Due to the recent development of MEMS(Micro Electro Mechanical System) [2], [3], [4], [5], [1] this concept becomes more feasible to manufacture many actuators at low cost. The system consisting of many actuators has not only above merits but also some inherent problems as follows.

1. **communication**
   To avoid large scale and complicated wiring problem of communication network, it should be assumed that the module can exchange information only with neighboring several modules.
2. **structure**
   The system is very suitable for homogeneous structure since the system composed of many actuators is fundamentally promised.

[1] MEMS is often characterized by miniaturization, multiplicity and microelectronics.

Distributed manipulation research is performed by many types of mechanisms at different scales from micro-scale [6], [7], [8], [9] to macro-scale [10], [11], [12]. Astronomical telescope "Subaru" composed of very large optical reflect mirror is well known as a great successful example of distributed manipulation.

II. Proposal of "Magic Carpet" composed of many actuators

For consideration of such distributed manipulation system, we set an explicit problem. The problem is to move an object put on the magic carpet to the target position. Each module of the magic carpet shown in Fig.1 can move along only z-direction [7].

Move an Object

$$(x_{ini}, y_{ini}) \Rightarrow (x_d, y_d)$$

where, (x_{ini}, y_{ini}) is the initial position of the object and (x_d, y_d) is the target position.

We consider actuator array on the xy-plane ($x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}$), which consists of m decentralized modules along x-direction and n along y-direction [8]. The function of each decentralized actuator module is given as follows.

- **sensor**
  The sensor detects whether anything exists on the module or not.
- **actuator**
  The actuator drives the module along z-direction and keeps it at any position.
- **microprocessor**
  The microprocessor can perform very simple calculation and communicate only with several neighboring modules.

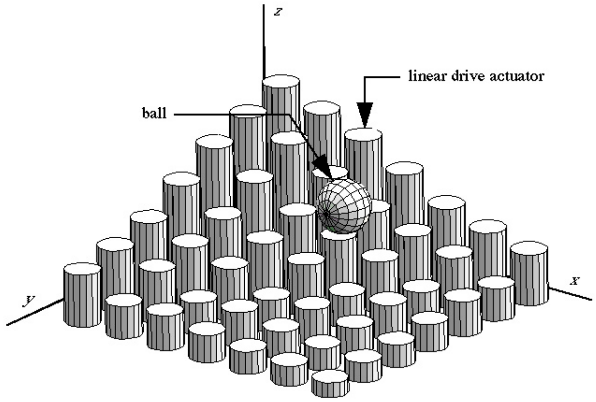

Fig. 1. Conceptual configuration of magic carpet. We try to realize this magic carpet in our real world.

III. Control Strategy

A. *Combined control of central / autonomous decentralized algorithms*

We apply the proposed "combined control of central / autonomous decentralized algorithms" to the magic carpet. Fig.2 shows its conceptual configuration. The central controller is allocated around decentralized modules. The modules have lattice structure. The operator commands only to the central controller. The central controller sends commands to the several neighboring modules close to the boundary. Each module is activated by communicating with neighboring modules.

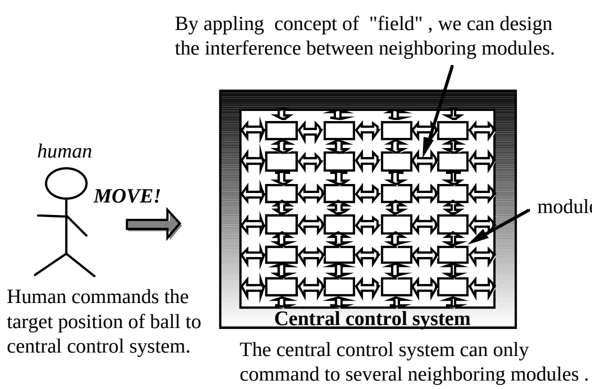

Fig. 2. Combined control of central / autonomous decentralized algorithms.

B. *Object position control algorithm based on feedback*

We have already proposed object transfer algorithm based on "feedforward" without object position estimation [11], [12]. Against this scheme, position response of the object can be dynamically designed using the feedback scheme. In this section, we propose object transfer algorithm based on "feedback" with object position estimation using the sensors attached to actuator modules. Fig.3 schematically shows the block diagram of this feedback based system. Three important parts as follows are included in this block diagram.

1. **behavior of actuator modules and decision of boundary condition**
   Each actuator module is activated only by local communication. The boundary condition is only external input to actuator modules. If this boundary condition is appropriately given, object position feedback control can be achieved.
2. **object position estimation by using the sensors**
   Object position estimation is essential to realization of object position feedback control(This estimation explicitly means where the object is on the carpet). The sensor is attached to sense object above each module and each module can only communicate several neighboring modules. Position estimation can be achieved using those two functions [9].
3. **design of feedback controller**
   Object position feedback controller is composed of PD controllers and disturbance observer in order to achieve robust object position control. By adjusting these controller's gains, object position response can be designed.

B.1 Behavior of actuator modules and decision of boundary condition

Actuator module should cooperate each other for achievement of object transfer. This cooperation should be realized by local communication to avoid complicated wiring problem. Therefore, the following Laplace equation (1) is adopted as the communication rule between actuator modules.

Here, z in (1) is position(or position command) along to z-direction and $z(x, y)$ means z of a actuator module allocated at (x, y). We assumed that the actuator modules are located with very high density enough to be dealt with in continuous space on the xy-plane.

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} = 0 \tag{1}$$

In practice, actuator modules are not allocated with enough density to deal them in a continuous space. As the result, the field value z exists only at the positions represented by

$$x_i = x_{\min} + i\Delta x \qquad (i = 0, \cdots, n_x - 1) \tag{2}$$

$$y_j = y_{\min} + j\Delta y \qquad (j = 0, \cdots, n_y - 1), \tag{3}$$

where Δx, Δy , n_x and n_y are the distance between modules and the number of modules in x and y-directions, respectively. The z is discretized as below.

$$z_{ij} = z(x_i, y_j)$$
$$= \left(\frac{2}{\Delta x^2} + \frac{2}{\Delta y^2}\right)^{-1} \left(\frac{z_{i-1,j} + z_{i+1,j}}{\Delta x^2} + \frac{z_{i,j-1} + z_{i,j+1}}{\Delta y^2}\right). \tag{4}$$

(4) rules the communication scheme between modules under the restriction of local communication and homogeneous structure. To decide z_{ij} in (4), boundary condition is required.

Next, boundary condition generation rule is considered. Since solution of (1) is well known harmonic function and has neither local minimum nor maximum inside the region, the boundary condition is decided by

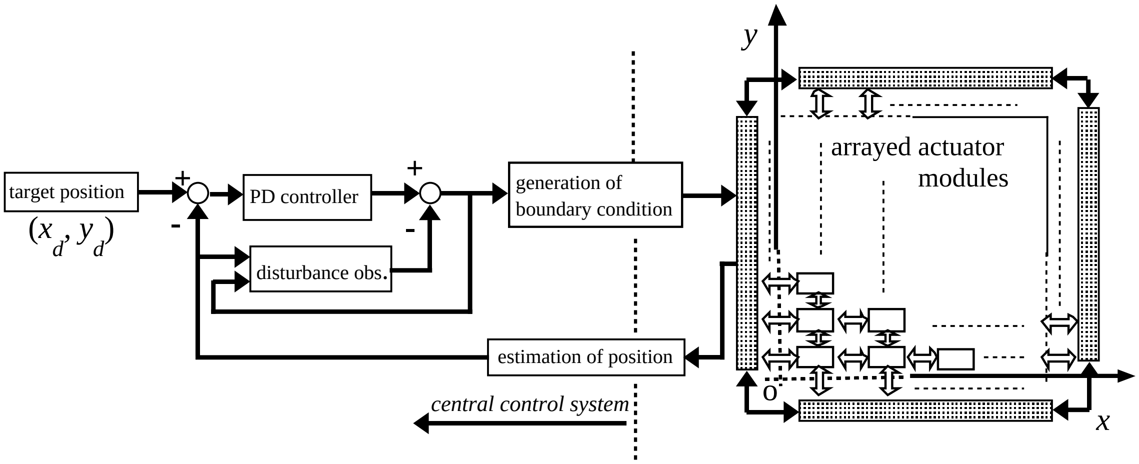

Fig. 3. Block diagram based on object position feedback control with object position estimation

- **case1** $(x_{obj} - x_d) > 0 \quad \& \quad (y_{obj} - y_d) > 0$
  $z(onBoundary3) = k(x_{obj} - x_d)$,
  $z(onBoundary1) = k(y_{obj} - y_d)$,
- **case2** $(x_{obj} - x_d) < 0 \quad \& \quad (y_{obj} - y_d) > 0$
  $z(onBoundary2) = k(x_{obj} - x_d)$,
  $z(onBoundary1) = k(y_{obj} - y_d)$,
- **case3** $(x_{obj} - x_d) > 0 \quad \& \quad (y_{obj} - y_d) < 0$
  $z(onBoundary3) = k(x_{obj} - x_d)$,
  $z(onBoundary4) = k(y_{obj} - y_d)$,
- **case4** $(x_{obj} - x_d) < 0 \quad \& \quad (y_{obj} - y_d) < 0$
  $z(onBoundary2) = k(x_{obj} - x_d)$,
  $z(onBoundary4) = k(y_{obj} - y_d)$,

where k and (x_{obj}, y_{obj}) are a positive constant and the object current position, respectively. Surface curve of the carpet generated by this boundary condition behaves like a plate. The object on the carpet rolls over and over.

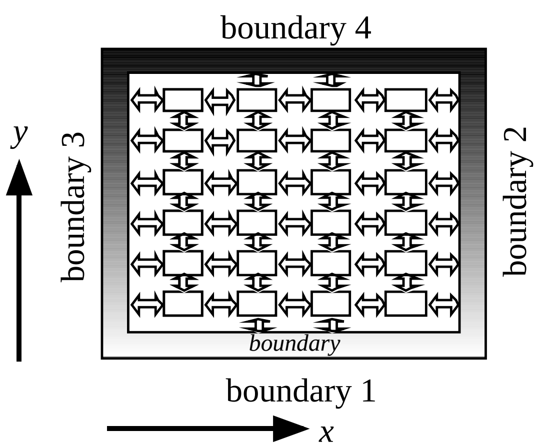

Fig. 4. Generation rules of the boundary condition

B.2 Object position estimation using the sensors

In this section, object position estimation by distributed scheme is considered. To move the object to the target position, current position is necessary information. By using the sensors, object position estimation can be achieved. Poisson equation (5) is employed as the field estimating the target position.

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = f(x, y) \tag{5}$$

Here, u in (5) is each module's internal state variable and is numerically realized in each actuator module. Of course, $u(x, y)$ means u of a module at (x, y). The right term $f(x, y)$ of (5) is proportionally determined by the sensor value at (x, y). If the variance of $u(x, y)$ on the boundary is monitored, the object position can be known. As is the case with z in (1), $u(x, y)$ is too discretized. Because actuator modules are not allocated with enough density to deal them in a continuous space.

B.3 Design of object position feedback controller

In the previous section, the boundary condition generation rules are already decided. Transfer function from the boundary condition input to the actual object position approximately becomes double integral form like (6) (The dimension of the boundary condition input has same of force.).

$$\begin{aligned} &\frac{p_x}{s^2}, \\ &p_x = \frac{1 + 2(x_{\max} - x_{\min})}{2(x_{\max} - x_{\min})^2} g \end{aligned} \tag{6}$$

To this plant model (6), object position controller consisting of PD controller and disturbance observer is attempted. If the PD controller is described as

$$K(s) = k_0 + sk_1, \tag{7}$$

the closed loop transfer function becomes

$$\frac{p_x k_0 + p_x k_1 s}{s^2 + p_x k_1 s + p_x k_0}. \tag{8}$$

If natural time constant τ_r and damping factor ξ of 2nd order lag system are employed, the gains k_0 and k_1 are described as

$$\tau_r^2 = \frac{1}{p_x k_0}, \quad 2\xi\tau_r = \frac{k_1}{k_2}. \tag{9}$$

To adjust these τ_r and ξ, characteristics of object position response is freely designed.

IV. Result

In this section, simulation results of the proposed feedback scheme are reported. Table I shows parameter used in simulation. Behavior of the object put on the carpet is simulated and shown in Figs.5-a and 5-b.

Fig.5-a is the time response(step response) of the object and shows that the object position converges to the target position (0.0975, 0.1625)[m]. Fig.5-b is the simulated trajectory of the object (◯ is marked every 500[ms].). Figs. 5-c, 5-d and 5-e show the surface curves of the carpet at 0.59[s], 1.79[s] and 4.14[s], respectively.

TABLE I
Parameters used in simulation.

Δx	0.065 [m]
Δy	0.065 [m]
n_x	8
n_y	8
$(x_{\min}, y_{\min})$	(0, 0)
$(x_{\max}, y_{\max})$	(0.455, 0.455) [m]
(x_{ini}, y_{ini})	(5.5Δx, 5.5Δy)=(0.3575, 0.3575) [m]
(x_c, y_c)	(1.5Δx, 2.5Δy)=(0.0975, 0.1625) [m]
τ_r	10 [s]
ξ	10

V. Conclusion

We proposed the combined control of central / autonomous decentralized algorithms in the realization of magic carpet. We have shown that the object can be transferred to the target position by object position control based on feedback, where object position is estimated only by communication with several neighboring modules. The conclusion is summarized as follow.

1. By adjusting the gains of PD controller and disturbance observer(object position feedback controller), object position response can be freely designed.
2. To realize this feedback, u in (5) concerning object position estimation is numerically realized in each module. As this result, object position estimation is achieved only to monitor u on the boundary.

VI. Future Works

In this paper, we have reported on the new object transfer system using this position feedback based on the object position estimation. Its effectiveness is only confirmed by simulation. We are now planning to add this function to the experimental setup. We will report on this experimental results in the workshop.

Appendix

I. Outline of the manufactured experimental setup

Experimental setup is manufactured to propose a distributed manipulation control algorithm for many modules' system. We manufactured experimental setup by using real world scale actuators. Fig.5 shows the rough sketch of the experimental setup consists of 64 decentralized modules. Figs.6 and 7 are controllers and actuators of magic carpet. This setup is composed by 64 actuators, 64 position controllers using sliding mode control and "one" personal computer(PC). 64 microprocessors are virtually realized by the PC. In other words, hardware configuration of the setup is central control type, but decentralized control is realized by software in the PC.

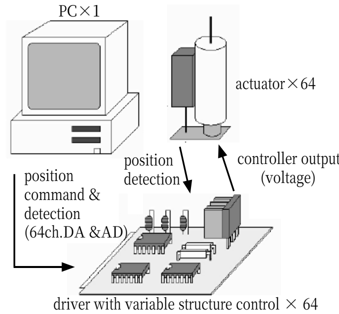

Fig. 5. Outline of the experimental setup consisting of 64 variable structure controllers, 64 linear drive actuators and "one" PC.

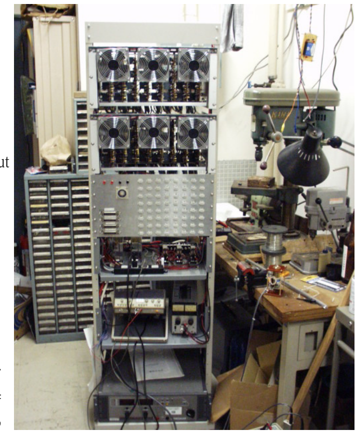

Fig. 6. Overview of the experimental setup including 64 controllers and main power supply.

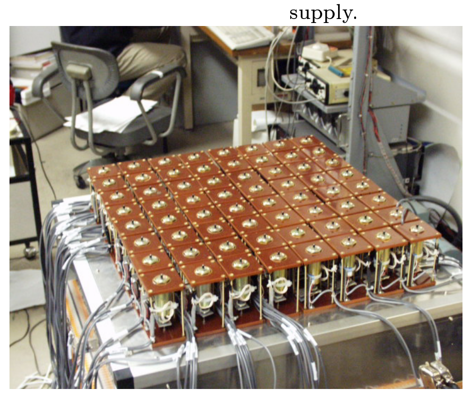

Fig. 7. A part of the experimental setup, arrayed many actuators on 2-dimensional plane

II. Position control of each actuator

Fig.8 shows a solenoid plunger with linear position sensor, which we selected as "modules" in trial manufacturing.

The structure of this solenoid plunger is shown in Fig.10. Electromagnetic force is calculated using the simple model in Fig.9 as electromagnetic model.

The force of the solenoid plunger takes the form of (10) using Ampere's integration law. It is inversely proportional to the square of position z and proportional to the square of current i.

$$f_e = -\frac{2\mu_0 N^2 \pi R^2}{(2dz + gR)^2} i^2 \tag{10}$$

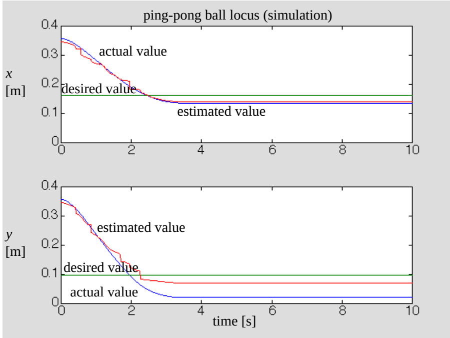

Fig. 5-a
TIME RESPONSE

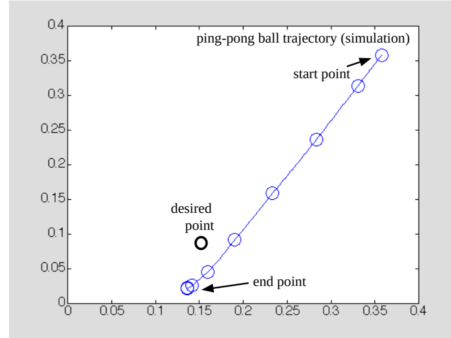

Fig. 5-b
TRAJECTORY

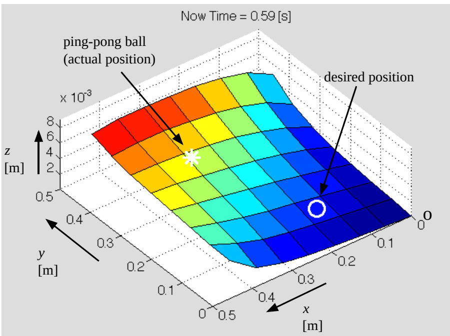

Fig. 5-c
SURFACE CURVE AT 0.59[s]

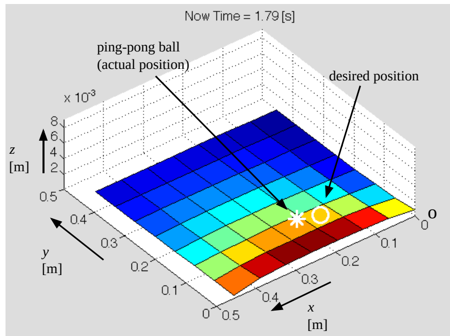

Fig. 5-d
SURFACE CURVE AT 1.79[s]

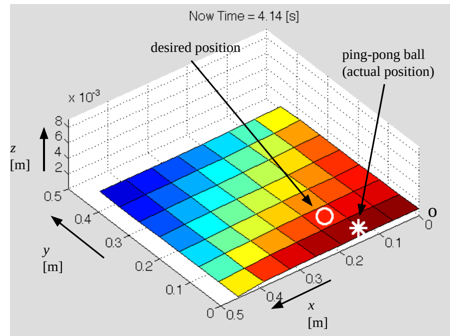

Fig. 5-e
SURFACE CURVE AT 4.14[s]

Fig. 8. The real world actuator module consisting of solenoid plunger. We can easily see attached position sensor. This position sensor is putted to use position signal in feedback controller.

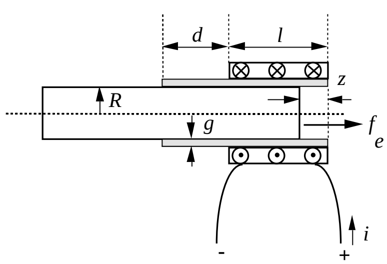

Fig. 9. Electromagnetic model of the solenoid plunger. Electromagnetic force generated in this solenoid plunger is calculated by using this simple model.

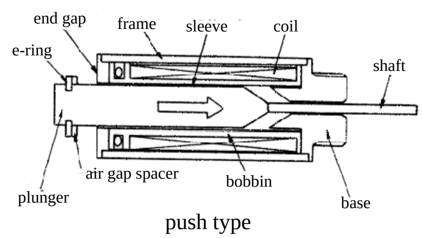

Fig. 10. Configuration of the solenoid plunger.

where, μ_0, N, R, g, π and i are vacuum permeability, turn number per meter, radius of plunger, gap length, the circle constant and solenoid current, respectively.

$$f_e = f_e(z^{-2}, i^2) \tag{11}$$

Because of high nonlinearity in force generation, position control of the solenoid is not so easy. We applied several robust control methods, and as the result, we selected variable structure control. Fig.11 and Fig.12 are its block diagram and analog diagram respectively. The comparator represents variable structure and high pass filter suppresses chattering of position z near desired position z^* in Fig.11.

The experiment and the simulation results of solenoid plunger position control are shown. Fig.13-b is the experimental position response driven by the analog circuit of

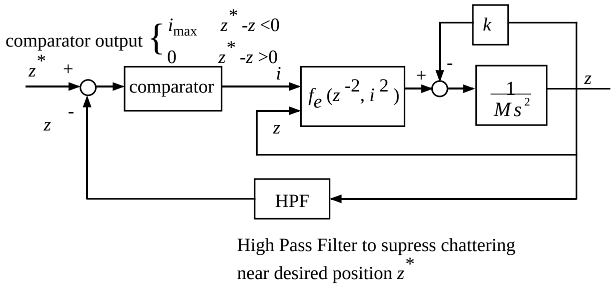

Fig. 11. Control system of solenoid plunger with variable structure controller.

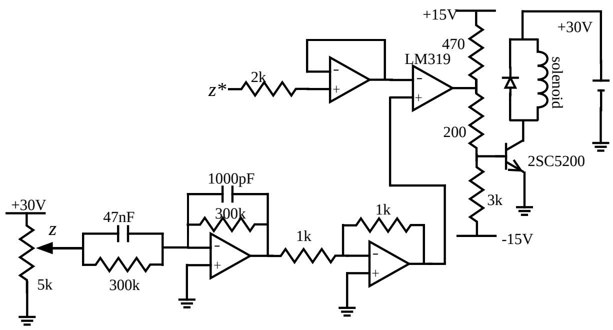

Fig. 12. Analog circuit of the variable structure controller. This variable structure controller actually used in the experiment. 64 sets of this analog circuit are prepared for realization of magic carpet. This circuit is very simple and adopted for position controller.

Fig.12 and Fig.13-a is the simulation results of position response. Upper figure in Fig.13-a is position response without high pass filter shown in Figs. 12 and 11 and Lower one is with high pass filter. We can see a good agreement between the command and actual positions and recognize to overcome nonlinearity of the solenoid plunger and to suppress chattering near the command position by using robust variable structure (sliding mode) controller and high pass filter.

References

[1] K.-F.Böhringer, Howie Choset, "Distributed Manipulation", Kluwer Academic Publishers

[2] Y. Nemoto, "On the Publication of an Issue on "Micro Machine", Jour. JSME, vol.97, no.905, pp.252, 1994 (*in Japanese*)

[3] Gabriel. K. J, "MEMS Research Project in U.S.A." , Jour. JSME, vol.97, no.905, pp.272-275, 1994 (*in Japanese*)

[4] H.Fujita, "Autonomous Distributed Systems for Micromachines", Jour. SICE, vol.32, no.10, pp.848-853, 1993 (*in Japanese*)

[5] H.Fujita, "Autonomous Distributed Micro Systems", Jour. JSME, vol.97, pp.298-301, 1994 (*in Japanese*)

[6] S. Konishi, Y.Mita, H. Fujita, "Two-Dimensional Conveyance System Using Cooperative Motions of Many Fluidic Microactuators", Jour. Advanced Robotics,vol.12, no.2, pp.155-165, 1998

[7] K.-F.Böhringer, B.R.Donald, R.Mihailovich, N.C. MacDonald, "A Theory of Manipulation and Control for Microfabrication Actuator Arrays", In Proc. 7th IEEE International Workshop on Micro Electro Mechanical System, pp.102-107, 1994

[8] J.W.Suh, R.B.Darling, K.-F.Böhringer, B.R.Donald, H.Bltes, T.A.Kovacs, "CMOS Integrated Ciliary Actuator Array as General-Purpose Micromanipulation Tool for Small Objects", Journal of Microelectromechanical Systems, vol.8, no.4, pp.483-496, 1999

[9] K.-F.Böhringer, V.Bhatt, K.Y.Goldberg, "Sensorless Manipulation Using Transverse Vibrations of a Plate", In Proc. the IEEE International Conference on Robotics nad Automation, pp.1989-1996, 1995

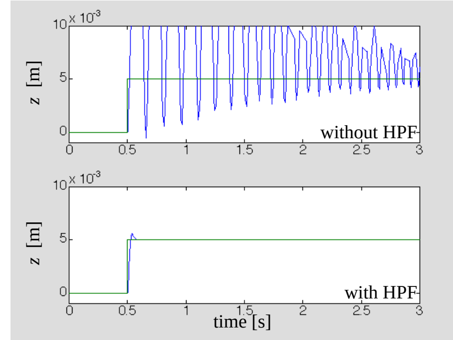

Fig. 13-a
Position response with variable structure controller(simulation). Upper figure is without HPF and lower one is with HPF.

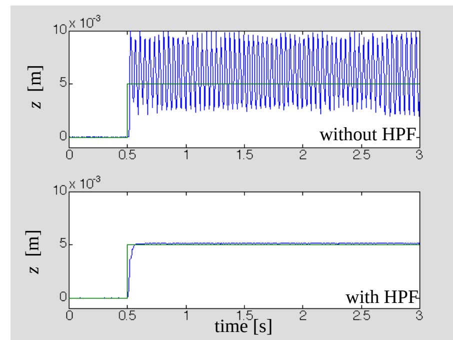

Fig. 13-b
Position response with variable structure controller(experiment).

Fig. 13. Position response with variable structure controller -

[10] J.Luntz, W. Messner, H.Choset, "Stick-Slip Operation of the Modular Distributed Manipulator System", In Proc. American Control Conference, pp.3853-3857, 1998

[11] H.Oyobe , H. Kitajima, Y.Hori, "Design and Realization of Autonomous Decentralized Object Transfer System:Magic Carpet", in Proc. 6th IEEE International Workshop on Advanced Motion Control, pp.25-29, 2000

[12] H.Oyobe, R. Marutani, Y.Hori, "Experimental Manufacturing of Object Transfer System "Magic Carpet" Consisting of Actuator Array with Autonomous Decentralized Control", in Distributed Autonomous Robotic System 4, Springer-Verlag, pp.437-446, 2000