Experimental Manufacturing of Object Transfer System "Magic Carpet" Consisting of Actuator Array with Autonomous Decentralized Control

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Abstract. The attempt to realize magic carpet driven by autonomous decentralized type control algorithm is proposed. The proposed system is manufactured as trial experimental setup and an experiment is done by itself. At last, a control algorithm for autonomous decentralized system is proposed. Due to the recent development of micromachine technology, we can integrate a lot of very small decentralized modules, each of which consists of sensor, actuator and electronic circuit. However, control algorithm of such systems have not yet been developed enough. To avoid complicated wiring problem of communication network, it is assumed that the module should exchange information only with neighboring several modules. The proposed system is manufactured for developing control algorithm of such system.

1 Introduction

Recent development of science and technology has realized a lot of things which have been drawn only in "SF" world. Micromachine is one of them. The submarine on the film "Fantastic Voyage" is often referred to as an example of future micromachine technology [1]. Micromachine is characterized by the following "3M" [2].

1. Miniaturization
2. Multiplicity
3. Microelectronics

Miniaturization means light and speedy action. Multiplicity means harmony of many micromachines. Microelectronics is important because semiconductor process technology is crucial in making micromachines. One micromachine module has actuator, sensor and electronic circuit like a microprocessor. As each micromachine module is very small and has poor ability, a lot of micromachine modules should be integrated to perform actual tasks [3] [4]. Micromachine technology has 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
   Semiconductor process technology is not good at making heterogeneous structure, but very suitable to make homogeneous structure.

As discussed above, micromachine modules must harmonize with each other. The proposed experimental setup is manufactured to develop a algorithm such that a micromachine module harmonizes with the other one [5].

2 Problem setting

For consideration of autonomous decentralized control system, we set an explicit problem. The problem is to move a ball 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 [6].

<u>Move the Ball</u>

$$(x_{ini}, y_{ini}) \Rightarrow (x_c, y_c)$$

where, (x_{ini}, y_{ini}) is the initial position of the ball and (x_c, y_c) is the target position.

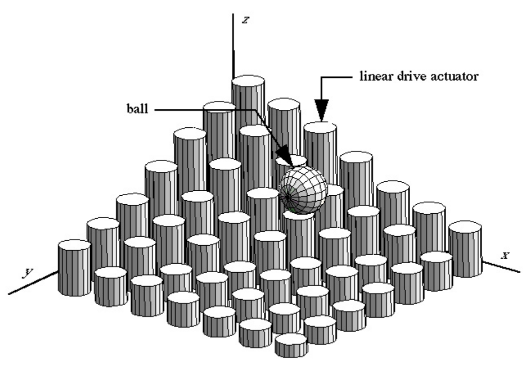

Fig. 1. Conceptual configuration of magic carpet. We try to realize this magic carpet in our real world.

We consider the micromachine 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 [7]. The function of each decentralized module is given as follows. The sensor detects whether anything exists on the module or not. The actuator drives the module along z-direction and keeps it at any position. The microprocessor can perform very simple calculation and communicate only with several neighboring modules.

3 Manufacturing experimental setup for the proposed system

3.1 Configuration of the setup

Experimental setup is manufactured to develop autonomous decentralized control for micromachine modules. Micromachine researches are now in developing. Our final goal is the realization of magic carpet based on micromachine technology, but it is not so easy to develop micromachine linear drive actuator at present. Whereby, we decide to manufacture experimental setup by using real world scale actuators. Fig.2 shows the rough sketch of the experimental setup consists of 64 decentralized modules. Figs.3 and 4 are controllers and actuators of magic carpet under manufacturing. This setup is composed by 64 actuators, 64 designed variable structure controllers and "one" personal computer(PC). 64 microprocessors are virtually realized by a PC. In other words, hardware configuration of the setup is central control and decentralized control is realized by software in the PC.

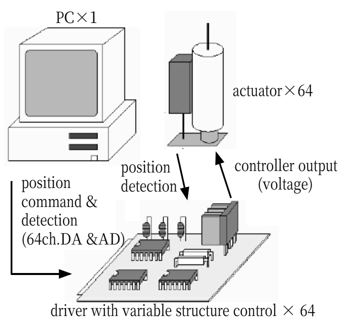

Fig. 2. Fundamental conceptual figure of experimental setup consisting of 64 variable structure controllers, 64 linear drive actuators and "one" PC.

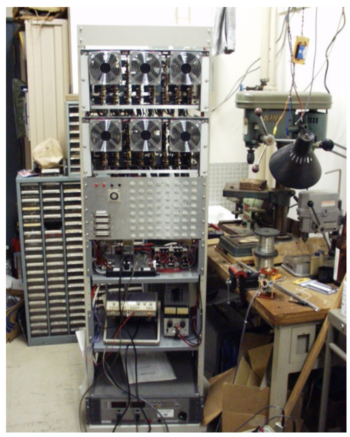

Fig. 3. Overview of experimental setup including 64 controllers and main power supply.

3.2 Design of position control for each actuator

A solenoid plunger is adopted as a real world actuator. The position (or force) control are implemented in each adopted solenoid plunger to realize linear drive actuator. Fig.5 shows the solenoid plunger. At first, we try to design position controller for the solenoid plunger. The structure of this solenoid plunger is shown in Fig.6. Linear position sensor seen in Fig.6 is attached with

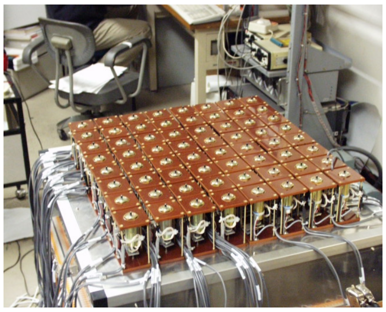

Fig. 4. A part of experimental setup, arrayed many actuators on 2-dimensional plane

Fig. 5. 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.

this solenoid plunger for position control. Electromagnetic force is calculated using the simple model in Fig.7 as electromagnetic model. The force of the

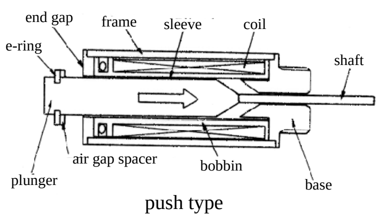

Fig. 6. Configuration of the solenoid plunger.

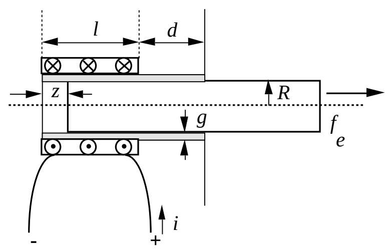

Fig. 7. Electromagnetic model of the solenoid plunger. Electromagnetic force generated in this solenoid plunger is calculated by using this simple model.

solenoid plunger takes the form of (1) using Ampere's integration law. It is inversely proportional to the square of position z and proportional to the square of current i.

$$f_e = -\frac{2\mu_0 N^2 \pi R^2}{(2dz + gR)^2} i^2 \tag{1}$$

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

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

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. Figs.8 and 9 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.8.

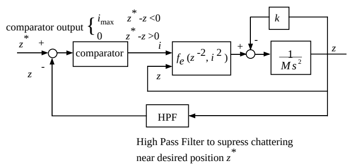

Fig. 8. Block diagram of solenoid plunger including variable structure controller and high pass filter.

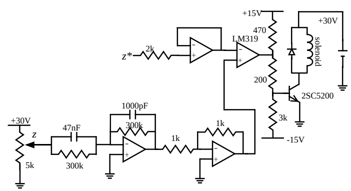

Fig. 9. Analog circuit of a variable structure controller. This variable structure controller actually used in the experiment. 64 sets of this analog circuit are prepared for realization of magic carpet. This circuit is very simple and adopted for position controller.

3.3 Position control for each actuator

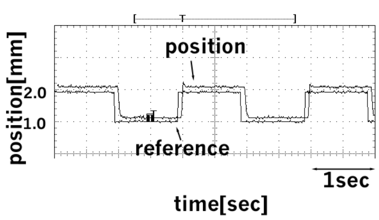

Fig. 10. Position response with variable structure controller. We can see a good agreement between the command and actual position.

In this section, the experiment results of solenoid plunger position control is shown. Fig.10 is the position response driven by the analog circuit of Fig.9. We can see a good agreement between the command and actual position and recognize to overcome nonlinearity of the solenoid plunger by using robust variable structure controller and high pass filter.

4 Object conveyance by the proposed system

We stand on the starting point of autonomous decentralized control research by completion of experimental setup. Experimental setup configuration is mainly reported in this paper. In this section, we consider to move the proposed system by autonomous decentralized scheme. At first, the proposed algorithm is divided into two steps: macro-scale and micro-scale, corresponding actuator array and actuator in itself. Micro-scale control is implemented in a robust manner by the variable structure controller. Macro-scale control is discussed in this chapter.

4.1 Concept of "field"

What is the concept of "field"? Generally speaking, autonomous decentralized system is a complex system composed of a lot of decentralized modules. However, its behavior can be divided into two steps. One is the micro-scale behavior of each module, and the other is the macro-scale behavior to rule many modules. For example, in our society, each human corresponds to a module and public opinion rules macro-scale behavior. Public opinion is a kind of "field". The micro behavior is relatively quick, and macro-scale behavior usually has a long time constant. Our proposal is to realize this "field" by central control.

4.2 Combined control of central / autonomous decentralized algorithms

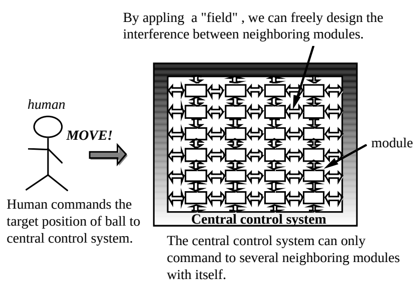

Fig. 11. Combined control of central / autonomous decentralized algorithms.

We apply the proposed "combined control of central / autonomous decentralized algorithms" to the magic carpet. Fig.11 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.

Here, it is clear that the central controller is in charge of macro-scale control, and each module is of micro control.

4.3 Control of macro-scale behavior

To convey a ball to the target position, we hit upon the idea of constructing ball position feedback control based on estimation of ball position at first. That scheme was already proposed [8].

As next step, ball conveyance without estimation of ball position by the proposed system is considered. An algorithm is quite simple. To convey a ball to the target position, the carpet makes a hollow. To do this, "each" module should know the target position and its own position. How does each module get these important information? It is discussed in this section.

It is easily known from the configuration of the system, the central controller gives the boundary condition. At first, we design the field to tell each module of its own position. If u^{xcd}, the field value, has the solution given by (3), each module can know its own position as follows.

$$u^{xcd} = \frac{x_{\max} - x_{\min}}{x_{\max}} x + x_{\min} \\ (x_{\min} \le x \le x_{\max}, y_{\min} \le y \le y_{\max}) \tag{3}$$

(4) is the field equation to give the solution (3). The field (4) can be realized only by local communication between modules.

$$\frac{\partial^2 u^{xcd}}{\partial x^2} + \frac{\partial^2 u^{xcd}}{\partial y^2} = 0 \tag{4}$$

To the central controller, (5) is given as the boundary condition.

$$u^{xcd}(x_{\min}, y) = x_{\min}, u^{xcd}(x_{\max}, y) = x_{\max}, \\ u^{xcd}(x, y_{\min}) = u^{xcd}(x, y_{\max}) = x \tag{5}$$

Next, the field to tell each module of the target position of the ball is designed. If u^{xc}, the field value, has the solution of (6), each module can know the target position.

$$u^{xc} = x_c \\ (x_{\min} \le x \le x_{\max}, y_{\min} \le y \le y_{\max}) \tag{6}$$

The field (7) gives the solution (6). Here, (7) can be realized only by local communication, too.

$$\frac{\partial^2 u^{xc}}{\partial x^2} + \frac{\partial^2 u^{xc}}{\partial y^2} = 0 \tag{7}$$

In this case, (8) is given to the central controller as the boundary condition.

$$\begin{aligned} u^{xc}(x_{\min}, y) &= u^{xc}(x_{\max}, y) = u^{xc}(x, y_{\min}) \\ &= u^{xc}(x, y_{\max}) = x_c \end{aligned} \tag{8}$$

(9) is the function to make a hollow at the target position (x_c, y_c). (u^{xcd}, u^{ycd}) shows the module position.

$$\begin{aligned} z(x, y) &= f(\boldsymbol{u}) = f(u^{xc}, u^{xcd}, u^{yc}, u^{ycd}) \\ &= \frac{\alpha_1 \left\{(u^{xcd} - u^{xc})^2 + (u^{ycd} - u^{yc})^2\right\}}{\alpha_2 \left\{(u^{xcd} - u^{xc})^2 + (u^{ycd} - u^{yc})^2\right\} + 1} \end{aligned} \tag{9}$$

The fields (4), (7) include no term concerning time domain. This means that each module acts independently.

5 Results

In this section, simulation and experimental results are reported. Parameters in Table 1 are used common in simulation and experiment. The hand-made experimental setup has capacity to perform an experiment by 64 (8x8) actuator arrays. Note that following experiment and simulation are done by 49 (7x7) actuators as shown in Table 1. This is caused by no large size rubber sheet coated on actuators shown in Fig. 15.

Table 1. Common parameters. The simulation and experiment are done with those parameters.

Δx	0.065 [m]
Δy	0.065 [m]
numb. of module (x)	7
numb. of module (y)	7
$(x_{\min}, y_{\min})$	(0, 0)
$(x_{\max}, y_{\max})$	(0.39, 0.39) [m]
(x_{ini}, y_{ini})	$(4.5\Delta x,\ 4.5\Delta y)$=(0.2925, 0.2925) [m]
(x_c, y_c)	$(1.5\Delta x,\ 2.5\Delta y)$=(0.0975, 0.1625) [m]
α_1	0.5
α_2	50

5.1 Simulation results

Behavior of the ball put on the magic carpet is simulated and shown in Figs.12 and 13. Fig.12 is time response of the ball and teaches that the ball position converges to the target position (0.0975, 0.1625) [m] with state error. This state error is caused by distance between actuators(Δx, Δy). The shorter this distance is, the smaller the state error becomes. Also the ball locus with vibration is quite natural. The implemented algorithm moves the ball by gravity. Fig.13 is a trajectory of the ball during the simulation. Figs.14-a, 14-b and 14-c show the surface curves of the magic carpet at the start 0.00[s], midstream 1.39[s] and end 9.79[s], respectively.

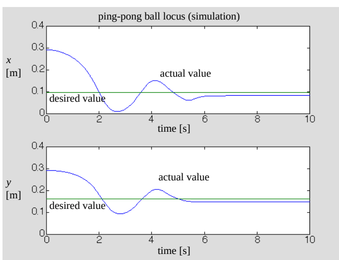

Fig. 12. Ping-pong ball locus (simulation). Upper figure is time response of ball position along x-direction. Lower one is about y-direction. The ball converges to the desired position with vibration.

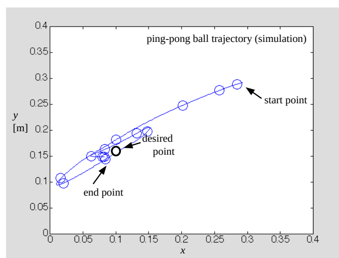

Fig. 13. Ping-pong ball trajectory (simulation). This figure is a ball trajectory obtained simulation results.

5.2 Experimental results

In this section, experimental results by the manufactured setup are reported. Parameters applied the experiment are same as those of the simulation shown in Table 1. Experimental procedure is quite simple. At first, a ping-pong ball is put at the initial position (0.2925, 0.2925)[m] (Fig.15-c). Then, the desired position (0.0975, 0.1625)[m] is set on the PC. Fig.15-a is the position

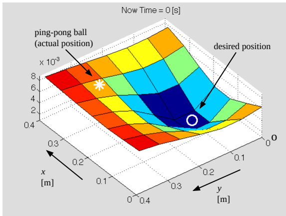

Fig. 14-a. Surface curve at 0.00 [s] (simulation)

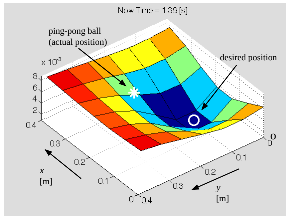

Fig. 14-b. Surface curve at 1.39 [s] (simulation)

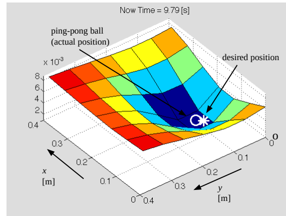

Fig. 14-c. Surface curve at 9.79 [s] (simulation)

Fig. 14. Magic carpet behavior (simulation) - interpolation curves between each actuator top - .

response of the ball. After 9 seconds, the ping-pong ball is carried to the desired position. The state error shown in Fig.15-a is caused by the same reason as that of the previous simulation. Fig.15-b is a trajectory of the ball. This experimental result corresponds to the simulation result of Fig.13.

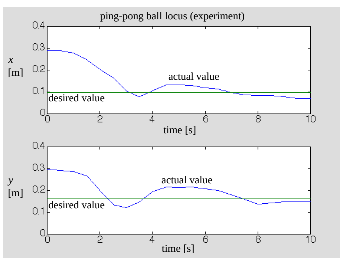

Fig. 15-a. Ping-pong ball locus (experiment). Upper figure is time response of ball position along x-direction. Lower one is about y-direction.

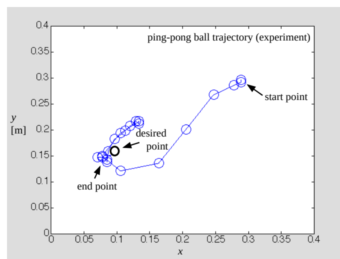

Fig. 15-b. Ping-pong ball trajectory (experiment).

6 Conclusion

We aim to construct object conveyance system composed by actuator arrays based on macromachine technology. In this paper, we mainly report

1. trial experimetanl manufacturing composed by actuator arrays
2. object conveyance algorithm development for such system
3. simulation and experimental results of the proposed system.

The experimental setup of the proposed system is manufactured in real size world. In order to realize this experiment, variable structure control of solenoid plunger position was applied and this position control succeeded. Also, we proposed the combined control of central / autonomous decentralized algorithms in the realization of magic carpet. The proposed algorithm

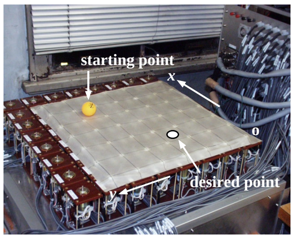

Fig. 15-c. Manufactured setup behavior before the experiment. The ping-pong ball is set at the initial point.

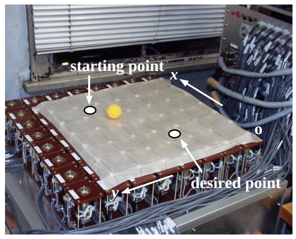

Fig. 15-d. Manufactured setup behavior during the experiment. The ping-pong ball is being carried to the target.

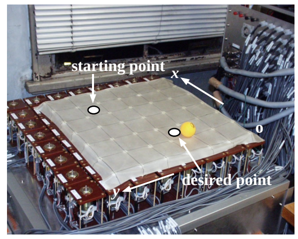

Fig. 15-e. Manufactured setup behavior after the experiment. The ping-pong ball has reached to the desired point.

Fig. 15. Magic carpet behavior (experiment) - An insufficient size rubber sheet covers the actuators.- .

overcomes the problems concerning communication and structure. We have shown that the object can be conveyed to the target position by making a hollow in the "field", where each module estimates the target and its own positions only by communication with several neighboring modules. The simulation and experimental results prove that the ball are carried.

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