Control Method for a 3D Form Display with Coil-type Shape Memory Alloy

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Abstract **- We previously proposed a new 3D form display actuated by shape memory alloy (SMA), which is capable of displaying large scale objects sequentially. Based on our devised method, our display uses a 16×16 array of pin-rods with 30mm stroke at 5mm intervals. In this paper, we discuss the control method of the shape memory alloy with a simple matrix drive circuit. This type of drive circuit can dramatically reduce the number of switch. In addition, we propose a novel approach using linear programming, where the simulated time to display a whole shape is reduced by about 50% or more with a large number of actuators.**

Index Terms – 3D Form Display, Shape Memory Alloy, Simple Matrix Drive Circuit, linear programming, Visual Tactile Display.

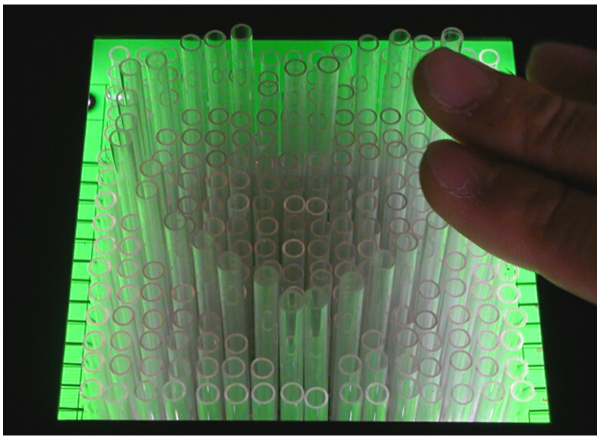


Fig. 1 The example of presenting shape (Heart shape)

I. INTRODUCTION

We previously proposed a novel 3D form display that is composed of an array of pin-rods actuated by coil-type shape memory alloy (SMA)[1]. The goal of this display is to present a large scale object with subtle expression based on densely arranged pin-rods. The stroke length for each pin-rod should be long enough to display an arbitrary shape like a geometrical feature or a human face. The movement of this display should be smooth enough to seamlessly change between displayed shapes. In addition, the number of pin-rods composing the whole display should be large enough for presenting very large objects like geographical features. We devised a method that satisfies these desired specifications, and developed an actual display composed of 256 pin-rods. Thus we can display arbitrary shapes as shown in Fig. 1. We can change the presented shape easily and touch the object's surface.

Perhaps the most complicated aspect of an SMA actuated display is the control method. Because of its dynamics, shape memory alloy cannot be driven instantly without a high applied voltage, and then it is difficult to control each pin-rod height with precise accuracy. Therefore, we need to develop a novel driving algorithm with a simple matrix drive circuit that is suitable for the eccentricities of SMA. In this paper, we overview the developed prototypes of the 3D form display, then describe our devised method, and finally evaluate its efficacy through simulation.

II. 3D FORM DISPLAY OVERVIEW

The proposed system to realize a 3D shape display is composed of four key elements: the actuator, pin-rod, positional sensor, and control circuit. We discuss each element in detail in the following sections.

A. Actuator

To achieve a dense display, the actuator for each pixel must be compact, so we use a kind of Shape Memory Alloy (SMA), material that can be stretched or deformed from its original shape, but would spontaneously return to its original shape when heated. However, conventional SMA can only extend its length by about 2-4%, which is not enough to realize our goal of a long stroke for each pin-rod.

Therefore, in our study, we use Coil-type Shape Memory Alloy (C-SMA) called Bio Metal Helix 200 (manufactured by Toki Corporation Co-Ltd.). This C-SMA is composed of SMA formed into a coil, and can therefore be extended up to twice its original length, and contracted to its original length by heating. A single strand of C-SMA is very thin (0.85mm in diameter), so it is possible to arrange densely in a pin matrix, while it has enough power to produce a 40-60gf force. We contract the C-SMA by simply applying an electric current to produce Joule heat. C-SMA is easy to extend when it is at room temperature, so we attached a spring to one end of the C-SMA, which constantly pulls the C-SMA, as shown in Fig. 2.

The range of motion depends on the C-SMA length. In the preliminary experiment for a 1m rod (42.1gf) with C-

SMA (750mm), the pin-rod is actuated at 500mm, and a longer length is possible for larger device units[1].

B. Pin-rod Configuration

The design of the pin-rod is just as crucial as the selection of the actuator for assembling a display with high density.

Fig. 2 illustrates our proposal for a pin-rod design. The pin-rod is composed of a cylindrical plastic pipe, which contains the C-SMA and circuit components as depicted in the figure. The C-SMA is fan-cooled, and it is important for each pin-rod to have sufficient aeration, so it has two pairs of slits facing each other, placed at right angles. This slit arrangement serves as a guide rail for motion, an entry point for current, and a window to control airflow.

Each pin-rod contains a diode for eliminating unintended loop current caused by simple matrix drive circuits[1][2][3].

C. Positional Sensing Method

Because the C-SMA itself only produces slightly detectable information related to its contraction, it is necessary to obtain the current position of the pin-rods with an external sensing method. Although it has been reported that the resistance change of simple SMA can be used for detecting its length[4], the actuator we use is coil formed, thus the model is changed after it has been actuated a few times. Therefore, we opted to pursue other methods to sense the actual position directly.

There are many ways to detect position, such as the use of a linear encoder[1], the inductance change of the coil[5], and the use of capacitance change[6]. However, the time and cost to construct the display increase dramatically by equipping a sensor for each pin-rod, and even very compact sensors occupy finite space, which greatly complicates the development of dense pin-rod arrays.

To solve this problem, we devised a method for detecting the pin-rod height through vision-based techniques. Each pin-rod has a colored marker on the bottom. The marker color is selected such that no adjacent pin-rods have the same color, in order to clearly distinguish a pin-rod from its neighbors in a captured image. We place a CCD camera on the inaccessible lower side of the display beside the pin-rods to capture their movement, as shown in Fig. 3.

In order for all markers to be visible to the camera, the length of the pin-rod increases according to its row number, and the length increments are determined depending on the maximum stroke of each pin-rod, which is given by the slit length mentioned in previous section. In this fashion, camera images forwarded to a PC can be used to compute all marker positions with a fast tracking algorithm, and the received state is processed as a height map of each pin-rod. Based on this height map, an appropriate control signal is issued according to the algorithm described in next section.

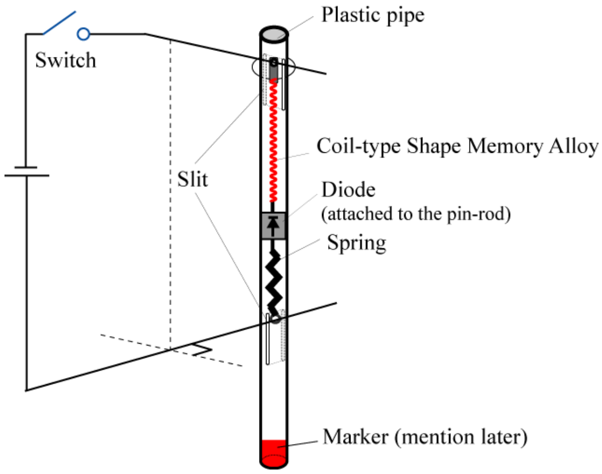
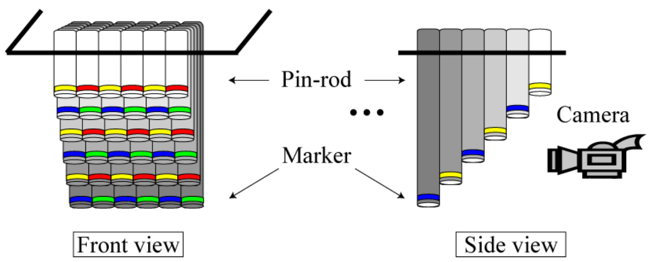


Fig. 2 Actuator & pin-rod configuration

D. Driving Circuit

We adapted a well-known simple matrix type circuit to drive electrical current through each pin-rod. Fig. 4 shows our adopted method, with linear switch arrays positioned perpendicularly at opposing ends of the pin-rod matrix. With this method, the amount of information required to drive the system is proportional to $2N$, where N is the number of pin-rods on each side of the array. This contrasts with the N^2 complexity for circuitry that drives each pin individually, which will be increasingly important as the size of the array increases[1][2][3].



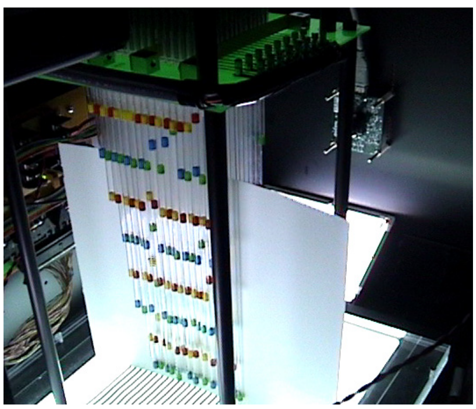


Fig. 3 Position acquiring method
Upper: Principle of measurement system
Below: Actual implemented system

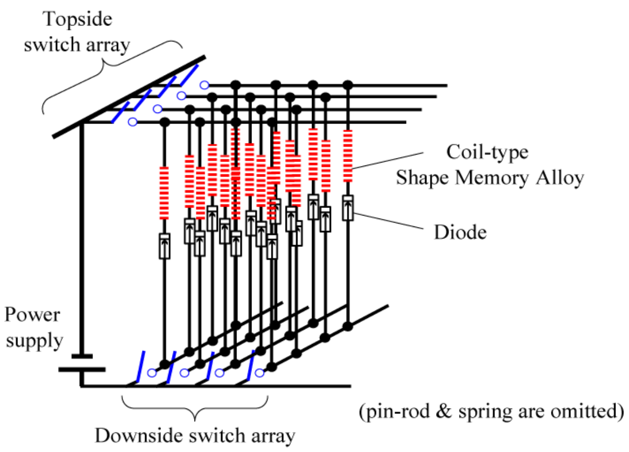


Fig. 4 Matrix drive circuit

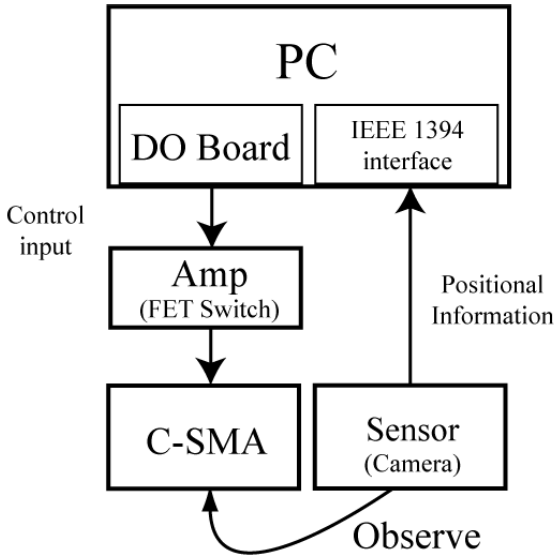


Fig. 5 Sytem overview

E. Developed Prototypes

Adapting these devised methods, we developed several prototypes, which could successfully display arbitrary shapes. Fig. 5 shows the system block diagram we developed in this project. A PC outputs the PWM signal for driving a FET as a switch, and adjusts the time-averaged voltage applied to the C-SMA. We use a VGA 640×480 color camera connected to the PC with an IEEE1394 cable, and the PC computes the pin-rod positions and feeds back a control signal to the C-SMA in the pin-rods. Each pin-rod is operated by this driving-measurement system, so it is possible to control an arbitrary number of pin-rods, given sufficient processing power. Pipes made of styrol resin (diameter: 4mm) were used as pin-rods, which were placed at 5mm intervals. The height of each pin can be controlled to 0.4mm intervals, granting the capability to display fine textures. We use a cooling fan to easily extend the C-SMA for each pin-rod.

This prototype was also designed to be touchable. As shown in Fig. 6, the pin-rod positions are detected in real time, so the corresponding CG model changed according to the operator's applied force. Unfortunately, C-SMA cannot produce enough power to present a sense of force, and the pin-rods were easily pressed down by hand. However, this malleability can be used as a form of 3D CAD, in which CG modelers may sculpt the displayed shapes directly by their own hand, without needing a conventional computer interface like a pointer device.

A second prototype was developed with the pin-rod array submerged in a container of oil to improve the response speed (Fig. 7). The prototype had no positional feedback, so pin-rods could only adapt an "on-off" state. Each pin-rod was made of bakelite, with the C-SMA sandwiched between thin bakelite plates. The pin-rod interval was also 5mm, and the pin-rod diameter was 4mm. The oil is cooled by a Peltier effect element placed at the bottom of the container, and is admixed to keep the oil temperature uniform. In this condition, the pin-rod can be actuated up to about 1 Hz with over 30 volts. Using a line-scanning method, the power consumption with oil cooling was about 1000 watts.

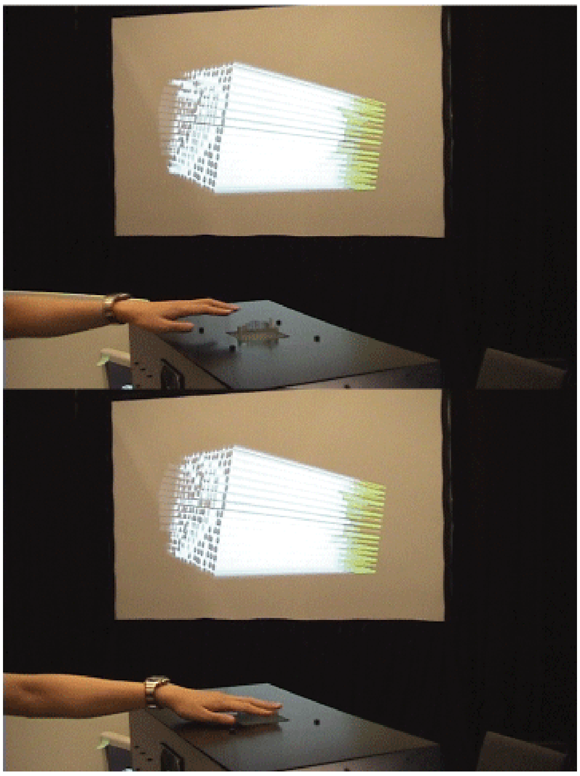


Fig. 6 Interaction with 3D form display
The model displayed on the screen is changed according to the operator's applied force.

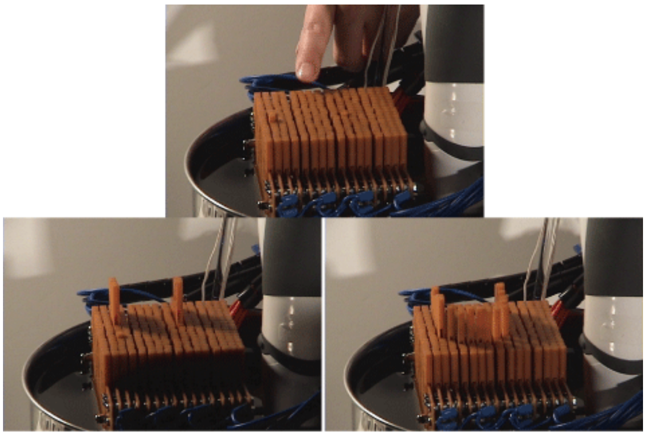


Fig. 7 Oil injected prototype for improving response time Character "U" is displayed rapidly.

III. CONTROL METHOD

A. Problem and motivation for a new driving method for simple matrix drive circuit

In the previous section, we described our developed system, which can present arbitrary shapes. However, there is one crucial problem in using a simple matrix drive circuit namely dynamics of SMA. It takes a long time to actuate every pin-rod to present one shape (about 5 – 10 seconds), which is undesirable for a form display that changes from one shape to another.

We have driven the 3D form display with a conventional line-scanning method commonly used for simple matrix devices such as a liquid crystal display. The line-scanning method iterates over every row in the array, and the signal lines are switched to contract the C-SMA of the pin-rods in the corresponding columns. This procedure is repeated until the pin-rod arrives at its desired position. Although this scheme appears reasonable, it does not work well in practice, because of the dynamics behavior of C-SMA, which changes its length about 30mm. If we adopted this scheme, it would take a long time to display only one shape because C-SMA cannot contract instantaneously.

The purpose of the scheme we propose here is to minimize the necessary time to actuate all pin-rods by accounting for the complex dynamics of each C-SMA coil. We seek a strategy to minimize the total time by maximizing the number of C-SMAs actuated with one set of control signal.

To state the problem mathematically, we first define several variables. We consider the problem of determining the optimal approach to drive an $n \times n$ matrix to match a shape S, represented as an $n \times n$ matrix of integer height values. According to the matrix drive circuit, control signals are realized as the dynamic transmission of two $n \times 1$ bit-vector control signals u and v.

The scanning line switch is denoted as:

$$\vec{u} = (u_1, u_2, \cdots, u_n)$$

The signal line is denoted as:

$$\vec{v} = (v_1, v_2, \cdots, v_n)$$

The components of each vector u_i and v_i are constrained to be within the set {0,1}, referring to switch states "open" and "closed", respectively. According to the circuit in Fig. 8, the product:

$$A = \vec{u}^T \vec{v} = \begin{bmatrix} u_1 v_1 & \cdots & u_1 v_n \\ \vdots & \ddots & \vdots \\ u_n v_1 & \cdots & u_n v_n \end{bmatrix} \tag{1}$$

depicts which pin-rods are actuated instantaneously by a given control signal pair. A has many variations, for example, when the dimension of u and v is 4, the number of unique combinations $\vec{u}^T\vec{v}$ can take is 225 + 1 (not 4^4=256 since $\vec{u}^T\vec{v}$ will be the zero matrix for 30 signal pairs), as shown in Fig. 9. When the dimension is 6, the total number of possible combinations is 3970, and when the dimension is 8, the total number is 65026.

We assume that the pin-rod does not descend after moving upwards until the displayed shape is completed.

We define a new $n \times n$ matrix B that represents the remaining change in height to display a shape. Here we reframe equation (1) by defining a new vector $\vec{a}$ and $\vec{b}$ composed of the components of respective matrices A and B, as follows:

$$\vec{a} = [u_1v_1, u_2v_2, \cdots, u_1v_1, u_2v_1, \cdots, u_nv_n] \tag{2}$$

$$\vec{b} = [B_{11}, B_{12}, \cdots, B_{1n}, B_{21}, \cdots, B_{nn}] \tag{3}$$

Here we define the time t applied to a switch state $\vec{a}$, where $\vec{a}$ is one of the possible switch state combinations. Then, the vector $\vec{b}$ is represented as:

$$\vec{b} = t_1\vec{a}(1) + t_2\vec{a}(2) + \cdots + t_m\vec{a}(m) = \hat{A}\vec{t} \tag{4}$$

where $\hat{A}$ is defined as $\hat{A} = [\vec{a}(1), \vec{a}(2), \cdots \vec{a}(m)]$. The maximum value m is the same as the total number of possible combinations. For example, when n=4, the value of m is up to 226 (Fig. 9).

Again, the desired goal is to minimize the total time to display a shape. In other words, we must minimize $t_1 + t_2 + \cdots t_m$. Consequently, the goal is represented as a linear programming problem as follows:

$$\vec{1} \cdot \vec{t} \rightarrow \min \tag{5}$$

subject to

$$\vec{b} = \hat{A}\vec{t} \tag{6}$$

$$\vec{t} \geq 0 \tag{7}$$

After this formulation, we can solve this problem by using standard linear programming library. We show a simple example for an 8×8 matrix. The height map can be realized with the switch combination shown in Fig. 10. In this example, linear programming method can realize the desired height map in half time as many as line-scanning method.

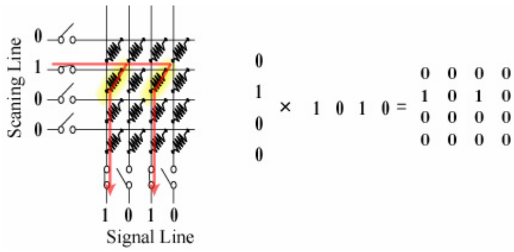


Fig. 8 Conventional line-scan method overview
Here we difine horizontal line is Scanning line, and vertical line is singnal line.

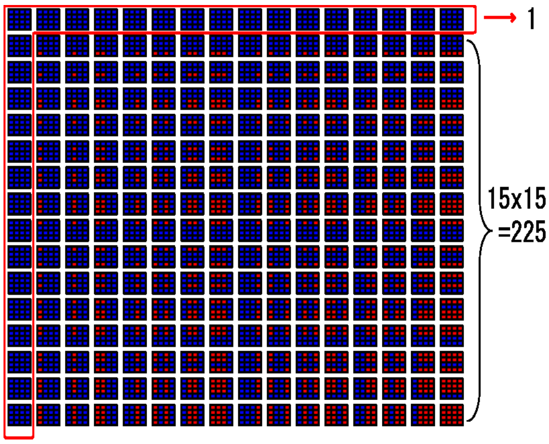


Fig. 9 Possible combination of pin-rod state (matrix size is 4 x 4). Blue square means "pin-rod is OFF," and red square means "pin-rod is ON."

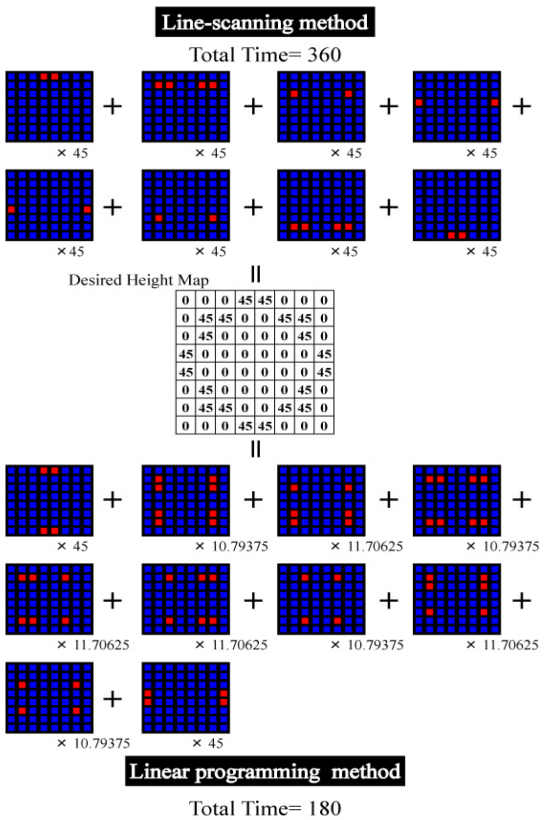


Fig. 10 One example of representing a circle with 10 switch states for an 8 x 8 pin-rod matrix by applying linear programming, contrary to 8 switch states for line-scnanning method. The number below each switch state indicates how long each switch state is applied. The total time for arriving desired height is shorter with linear programming method.

B. Evaluation

In this section, we evaluated the proposed algorithm by comparing with conventional line-scanning method

We simulated the time that is needed for arbitrary height map, which is given a pin-rod matrix. We consider square matrices with sizes ranging from 1×1 to 8×8. The goal height map was given as a uniform random distribution. Each height value was an integer from 0 to 100.

We executed the simulation 1000 times for each matrix size. The result is shown in Fig. 11. With line-scanning method, the average required time increases proportionally to matrix size, which is naturally expected result of the line-scanning method. On the contrary, with the linear programming method, the average of required time increases according to the square root of matrix size. The standard deviation of required time for the linear programming method does not dramatically change. This result indicates that as the size of matrix increases the linear programming method can display arbitrary shapes in a shorter time than with the line-scanning method. When the matrix size is only 8, the required time is reduced by an average 56%, and at a maximum of 65.5% in our simulation data.

IV. Discussion and Conclusion

In this paper, we presented a 3D form display using a dense array of pin-rods actuated by SMA, and discussed its control method for a matrix drive circuit. With our proposed method, we can display arbitrary shapes with significantly less time than with a conventional line-scanning method. We showed that our method is effective, and in 8 by 8 matrix, it can reduce the required time by more than 50 %.

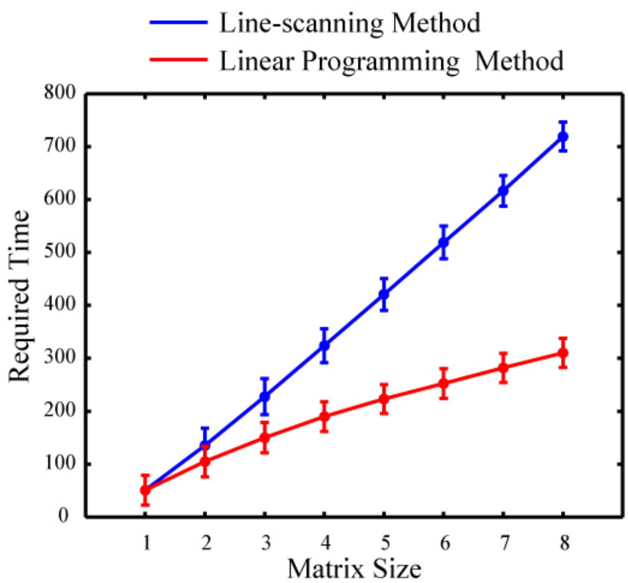


Fig. 11 Simulation result of matrix size versus required time
The matrix is assumed to be square.

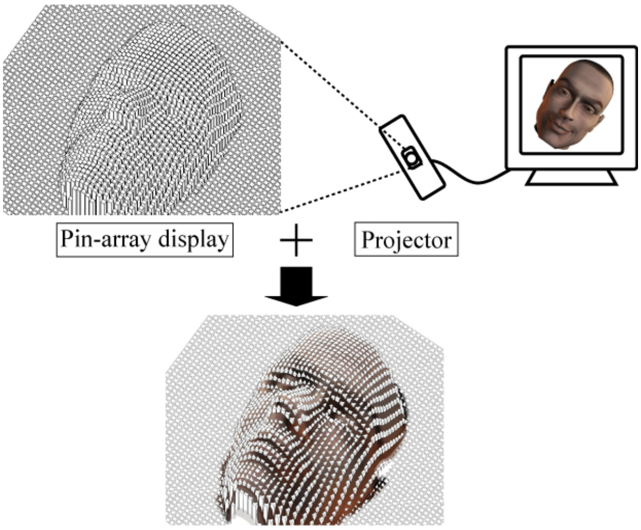


Fig. 12 One example of future applications
Pin-rods matrix presents a rough shape, and a precise texture is projected on to it. With this device, it is possible to see and touch the presented object with sense of physical presence. This application can be used as a kind of video conference system for displaying the presenter's (face) movement or dynamic demonstrations.

In a future paper we shall discuss the implementation of this control method for an actual device. Although we have simplified the situation by neglecting the C-SMA's dynamics, we must consider the dynamic behavior of C-SMA, including its hysteresis and cooling condition. In our next work, we will take the behavior model into account.

The fundamental problem that already arose is calculation time. While this approach always yields the optimal result, a brute force approach to the combinatorial optimization problem is infeasible for real-time display or for matrix sizes much larger than 8. To realize this type of 3D display with real-time motion or larger matrix sizes, there are two alternatives. The first is to decompose the larger matrix into blocks, and apply the linear programming method for each block. However, the benefit of linear programming over the line-scanning method would not be very significant for large displays. The second alternative is to obtain an approximate solution to the combinatorial problem based on heuristics. For instance, a method based on image compressing can be applicable, in which the height map corresponds to the intensity of a grayscale image. One possible candidate is the so-called Semi-Discrete Decomposition (SDD), an iterative greedy algorithm that represents an arbitrary matrix as the weighted sum of outer products of vectors whose elements are constrained to the set $\{-1, 0, 1\}$[7]. This algorithm was shown to compress grayscale images by an order of magnitude and is quite fast. Further, it can be adapted to our problem rather easily, as we shall describe in a future paper. Therefore, we can choose from the two ways, a strict linear programming method to obtain an optimal solution offline, or a fast but sub-optimal method for real time control.

The scalability of this display is perhaps the most disputable issue. In our prototype, we realized a 16 by 16 pin-rods matrix, and we believe it is possible to construct a larger system up to 32 by 32 pin-rods matrix with our proposed method. When the number of pin-rods is increased, one problem will arise. The problem is the power consumption of the system. When the C-SMA is actuated using PWM and relaxed by air-cooling, the power consumption is only about 200 Watts. However, with the cooled oil-injected condition for fast response, it has significantly higher power consumption, roughly five times as much. Therefore, we must consider the maximum power supply as a constraint in the adopted driving method. With the line-scanning method, it is difficult to take this limitation into account for driving the system. On the other hand, with the linear programming method, the maximum performance of the power supply can be taken into account as an inequality condition of linear programming.

As a near-future application, we will improve the visual aspect of the display. If we use optical fiber as a pin-rod, and project visual image or real-time movie from the bottom of the pin-rods matrix, it would become actual 3D television (Fig. 12). The display can also be used as a street advertisements or showcases. Since this display is touchable, and image is rear projected through optical fiber so the image is not disturbed by the operator's hands. Finally we will obtain an ultimate 3D shape display, both visually and haptically. This advantage can be used where natural representation is needed, especially in the field of Virtual Reality.

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