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# Dimensionality reduction of cellular actuator arrays using the concept of synergy for driving a robotic hand

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*Abstract* – **This paper presents a method of reducing dimensionality of cellular actuator arrays. The cellular actuator arrays are used to drive a multi-axis system, i.e. robotic hand. The actuator arrays use Segmented Binary Control(SBC) which simplifies the control of nonlinear artificial muscle actuators. Although the SBC simplifies the control, the number of cells required to create motions is increased dramatically, thereby increasing the dimension of the actuator arrays. Therefore, reducing the number of controls, or dimension is needed. The coordinated motion of the robotic hand enables the coupling of actuators. In biological systems, synergies, a strategy of grouping output variables to simplify the control of a large number of muscles and joints is used to explain the coordinated motion created by the muscles. Similarly we can apply this concept to group the cells of the actuator array to be turned on or off together. Each group of cells, called segments can be designed to perform a certain set of desired postures.**

**Data from fifteen different tasks is used in the design. The gathered joint angle data is transformed into actuator displacement data and used to generate a segmentation design of the actuator. For segmentation design, feature extraction method, similar to non-negative matrix factorization with binary filter is proposed. The segmentation design reduces 96 separately controlled segments to 6, while maintaining the ability to accomplish all desired postures. A prototype robotic hand with five fingers, designed and fabricated using the FDM process, is driven with this actuator system.**

## I. Introduction

Artificial muscle actuator is an actuator which has similar characteristics as biological muscles. They create motion by shrinking or expanding the material itself. Due to its lightweight and compact characteristics and limited displacement and force characteristics, it is likely that multiple of these artificial actuators will be used to drive a single joint, just like the biological muscles. For example, there are 13 muscles attached to frog hind limb [2]. When multiple actuators are connected to drive number of joints less than the number of muscles, there needs to be a strategy of driving complex actuators in a simple manner. Biological muscles have similar issues, and a concept of synergy is used to explain the simplified construction of motor behavior[1]. Bizzi et al[2,3] developed a new method to extract invariant spatiotemporal components from the simultaneous recordings of the activity of many muscles. They used this technique to analyze the muscle patterns of intact and unrestrained frogs during kicking. They showed that combinations of three time-varying muscle synergies underlie the variety of muscle patterns required to kick in different directions, that the recruitment of these synergies is related to movement kinematics, and that there are similarities among the synergies extracted from different behaviors. Santello et al[4] did a similar research with human hand. According to their research, a wide variety of hand shapes can be characterized as a weighted combination of just two or three main patterns of covariation in joint rotations, or "postural synergies.", since humans have limited ability to independently control the many joints of the hand. They also tried to align muscle synergies with these main postural synergies and describe the form of membership of motor units in these postural/muscle synergies [5]. Seventeen joint angles and the electromyographic (EMG) activities of several hand muscles were recorded while human subjects held the hand statically in 52 specific shapes (i.e., shaping the hand around 26 commonly grasped objects or forming the 26 letter shapes of a manual alphabet). They used principal-components analysis to reveal several patterns of muscle synergy, some of which represented either coactivation of all hand muscles, or reciprocal patterns of activity in the intrinsic index finger and thumb muscles or in the extrinsic four-tendon extensor and flexor muscles. Although usage or principal component analysis raises question about how they can be actually implemented in biological systems due to their negative values, it is interesting to see that wide variety of hand shapes can be represented by limited number of synergies.

Fig. 1 illustrates an artificial muscle actuator system having a cellular array structure. The rectangular blocks represent cellular building blocks that can be actuated individually and that are connected in series and parallel to move specific points along a linkage of bones. Unlike traditional electric motors, which can rotate infinitely in the absence of mechanical stoppers, the displacement of a muscle actuator is finite. The total displacement of the artificial muscle is determined by the integral of strains distributed over the individual building blocks in series. The output force is the summation of the forces generated at the individual strands arranged in parallel. These output characteristics can be tailored to specific load conditions by arranging the cellular building blocks in various patterns and activating them in a coordinated manner.

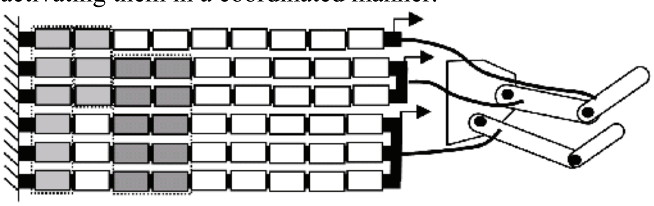

Fig. 1 Schematic of a multi-axis artificial muscle actuator array

In this paper, concept of synergy – coherent activations, in space or time, of a group of muscles – is used to simplify the design of a multi-axis cellular actuator using artificial muscle actuator, i.e. SMA.

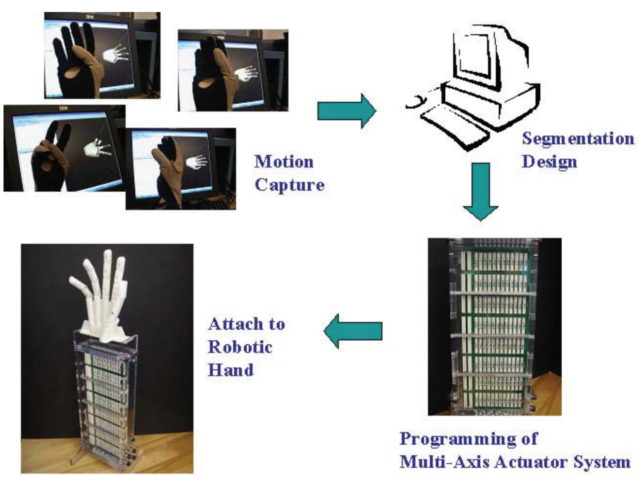


Fig. 2 Overview of the design procedure of multi-axis actuator array for driving robotic hand

Fig. 2 shows the overview of the design procedure for multi-axis cellular actuator array. First, postures to be performed by the robotic hand are captured with a cyber glove, a device that captures joint angles of the hand. Using the captured data, the cells of the actuator array that can be grouped and activated together is identified. Each group or segment is activated with a single drive amplifier. This segmentation design is implemented to the multi-axis cellular actuator system by wiring the cells such that all the cells in each segment can be activated with a single drive amplifier. This actuator array is connected to a five fingered robotic hand and drives the robotic hand to perform the fifteen hand postures.

## II. Algorithm

The cost function used to quantify the quality of the approximation can be constructed using the square of the Euclidean distance between matrix M and multiplication of matrix W and H. This is lower bounded by zero and becomes zero when M = WH.

$$\|M - WH\|^2 = \sum_{ij} (M_{ij} - (WH)_{ij})^2 \tag{1}$$

The following update rules are used to update the W matrix and H matrix iteratively. The Euclidean distance is non increasing under these update rules.

$$W_{ia} \leftarrow W_{ia} \frac{(MH^T)_{ia}}{(WHH^T)_{ia}} \qquad H_{aj} \leftarrow H_{aj} \frac{(W^T M)_{aj}}{(W^T WH)_{aj}} \tag{2}$$

The additional constraint of making the H matrix a binary matrix is applied after each update of the W and the H matrix according to the update rules (2). The idea is to filter the H matrix so that the values of the matrix elements go to either one or zero. For this purpose, sigmoid function in Eq. (3) is used as a filter.

$$S(x) = \frac{1}{1 + e^{-k(x-0.5)}} \tag{3}$$

where $x$ is the element of the H matrix, and $k$ is a variable that changes with every update, starting from 5.5 to 100. This variable change increases the slope of the sigmoid function, making it steeper as the update proceeds. At the last update, all the elements of H matrix are either zero or one.

## III. Application to Robotic HAnd

Fig. 3 Fifteen robotic hand postures used in the design. Joint angles for each posture are captured using the cyber glove and transformed into joint angles for the robotic hand.

Fifteen hand postures that are used frequently in everyday life were chosen. Fig. 3 shows the hand postures that were captured using the cyber glove and transformed into robotic hand postures. Joint angles from the cyber glove are transformed into joint angles for the robotic hand. Due to the limitations of the robotic hands,

These fifteen postures are used in the design of the segmentation.

Fig. 4 shows the graph of the norm of the error matrix as the number of segments used in the segmentation design changes. As the number of segments increase, the norm of the error is reduced. The selection of the number of segments will depend on the amount of error allowable for the design. By adding a compliant material on the robotic hand, we can allow certain amount of error on the grasp and still be able to use the robotics hands for grasping purpose.

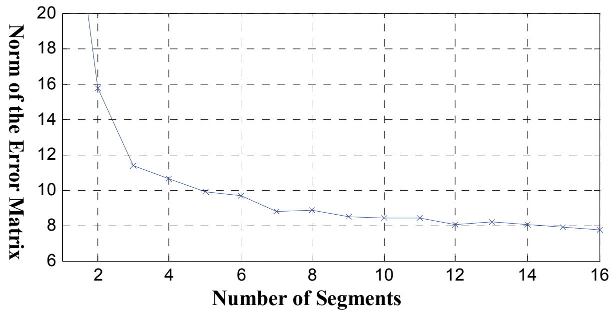


Fig. 4 Euclidean norm of the error matrix with regard to the number of segments.

We have chosen to use total of six segments in our design. Fig. 5 shows the 6 different hand postures that represent the six segments used in the design. By combining these six grasps, all fifteen grasps can be generated.

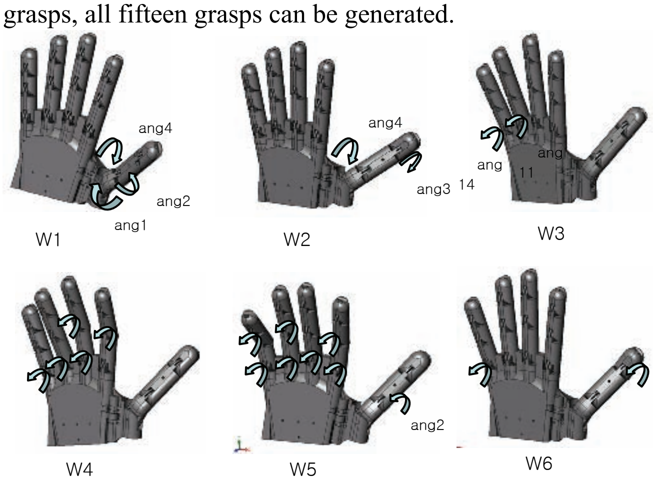


Fig. 5 Robotic hand representation of the six segments. Each grasp represents the posture of the robotic hand when a single segment is activated. All fifteen postures can be generated by combining these six grasps.

Fig. 6 shows the design of the actual segmentation of the actuator. Y axis represents each actuator, showing total of twelve actuators, and the color coded bar graph represents segments.

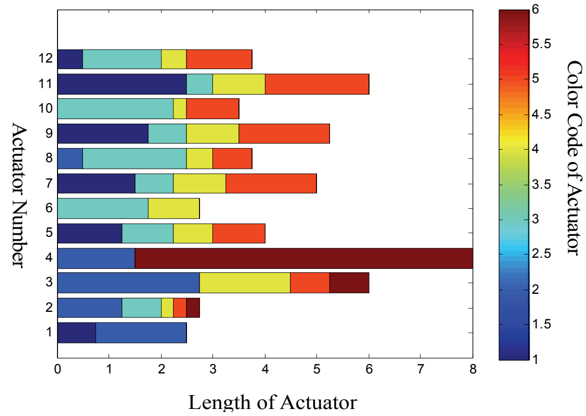


Fig. 6 Cellular actuator array grouped into 12 clusters

Fig. 7 shows a picture of fourteen postures while capturing the data, the robotic hand posture using the captured data, and generated robotic hand posture using the segmentation design. The difference of the grasps is the errors caused by the segmentation design.

Fig. 7 pictures of data capture using cyber glove, robotic hand posture created with actuator without grouping of the actuators, and robotic hand posture created with just 6 clusters. 14 different hand postures are used.

Fig. 8 shows the mean of the error of each joint and the standard deviation. On average, each joint angle has about 10degrees of error. In order to use this robotic hand for actual grasping purpose, the amount of error has to be limited.

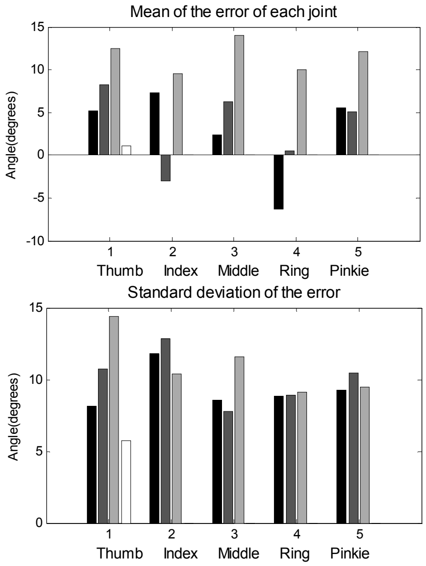


Fig. 8 mean of the error of each joint created by the actuator with clustering. (below) Standard deviation of the error

## IV. PROTOTYPE

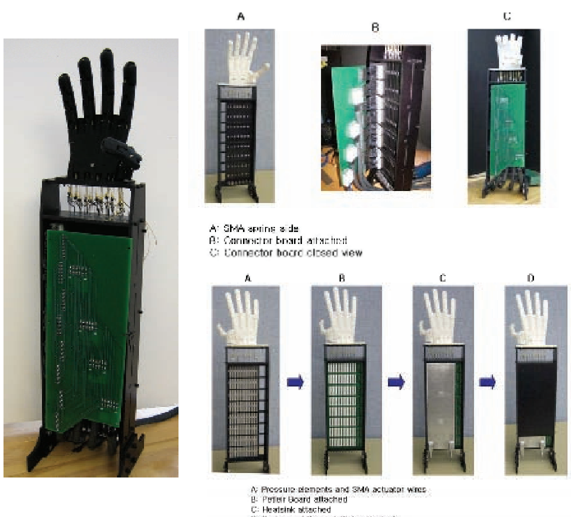


Fig. 9 Picture of the five fingered robotic hand that uses cellular actuator array with twelve axes.

The designed actuator system is attached to a robotic hand with five fingers. Each finger has three joints, where two joints, the PIP and the DIP are coupled. The thumb has two joints that bend toward the palm and one joint that rotates the thumb perpendicular to the palm. Fig. 2 shows the picture of the assembled robotic hand with actuator system attached. Two SMA actuators are connected to each finger, one at the end of the finger tip, and another at the end of the bone that is closest to the palm. These SMA actuators are pulled to bend the finger at the PIP and the metacarpophalangeal (MCP) joint, the joint that is closest to the palm. Fig. 9 shows the prototype of the actuator array and the robotic hand.

## V. CONCLUSION

In this paper, we have proposed an algorithm of reducing the dimensionality of the cellular actuator array. We group the cells to be activated together, just as biological systems group the muscles to be activated together to create a coordinated motion.

## VI. ACKNOWLEDGMENT

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