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SBC Hand: A Lightweight Robotic Hand with an SMA Actuator Array implementing C-segmentation

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***Abstract* – This paper presents a lightweight robotic hand that uses an SMA actuator array. The SMA wires are activated via joule heating, implementing SBC. A coordinate transformation architecture which reduces activation signal dimensionality, known as C-segmentation, is presented. A robotic hand with 16 controlled DOF and 32 independent SMA axes was developed to demonstrate the advantages of joule-heated SBC; the total weight of the robotic hand system was less than 800 grams. 16 different grasping postures were successfully recreated by using only 8 C-segments. It was concluded that a very lightweight robotic hand with simple controls can effectively reproduce the necessary configurations for conventional grasping situations.**

Keywords: Robotic hand, actuator, synergy, grasps

I. INTRODUCTION

The hand is perhaps the most sophisticated part of a humanoid robot, with many degrees of freedom required to reproduce the diverse postures and grasps that the human hand can perform. Due to limitations caused by the currently implemented actuators, many robotic hands are either too bulky or driven by less actuators, using a coupling mechanism or simplified design [1-3]. Artificial muscle actuators will enable us to increase the number of DOF in robots. Artificial muscle actuators are lightweight, compact, and have large power to weight ratio. Many new artificial muscle actuators are currently being developed [4-6]. There are several issues in the implementation of these artificial muscle actuators for driving systems of numerous DOF. One of them is the inherent nonlinearity of the artificial actuator material, which makes it hard to control. We have proposed a new approach of controlling artificial muscle actuators, called *Segmented Binary Control* (SBC) [7,8]. Instead of controlling the actuator as a single unit, this method divides the actuator into several segments, and controls each segment using a simple ON-OFF control.

Another issue is the complexity of controlling many DOF. As the number of DOF increases, the complexity of controlling these DOF increases exponentially. It is interesting to look into how biological systems handle the complexity of controlling many muscles to create motions. We have adapted the concept of synergy – coherent activations, in space or time, of groups of muscles – to simplify the design of a multi-axis cellular actuator array using artificial muscle actuators [9].

The concept of synergy is similar to concept of transforming the original data into a new coordinate system. By intelligent choice of the coordinate system, the dimension of the coordinate system can be reduced. Fig. 1(a) shows a set of data on a 3-dimensional space. Methods such as principal component analysis can be used to find new coordinates that can recreate the information with fewer dimensions. The output points can now be represented on a two-dimensional space as shown in the right. An effective reduction of dimensionality is possible only when the data is highly correlated or coupled.

Likewise, for a multi-axis actuator system that performs a highly correlated/coupled task, dimensionality can be reduced by grouping segments of actuators. A co-activated group of segments is referred to as a *C-segment*. Fig. 1 (b) shows three actuator axes where the output displacement can be plotted on a 3-dimensional space. The same outputs can be generated with two C-segments. These C-segments correspond to the new coordinate system.

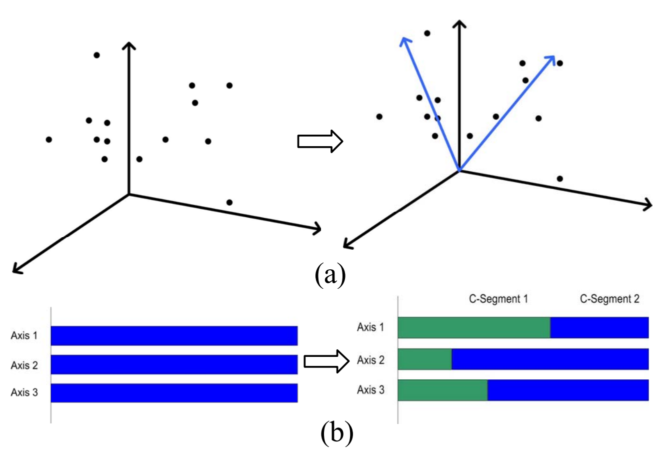

Fig. 1 Concept of dimensionality reduction using C-segments

As seen from research, there is much coupling in the motions of the human hand [10,11]; the C-segment concept can therefore be applied to reduce the complexity of control. Using a C-segment approach, all of the postures and grasps required for daily chores can be reproduced with just a few control signals; all 16 actuators can be controlled with only 8 C-segments, producing a total of 256 distinct postures.

By using the concept of SBC and C-segments, a lightweight robotic hand with shape memory alloys has been developed. The hand was designed to mimic the functionality of the human hand, which includes an underactuated design. The hand itself has 20 degrees of freedom, only 16 of which are controlled. This underactuation allows for more simple grasping algorithms. The unilateral nature of artificial muscle actuators causes the need for an antagonistic setup. Even with a total of 32 independent artificial muscle actuators, the entire apparatus as shown in figure 2 still weighs under 800 grams, including mechanical components, cooling devices, onboard electronics, and actuators.

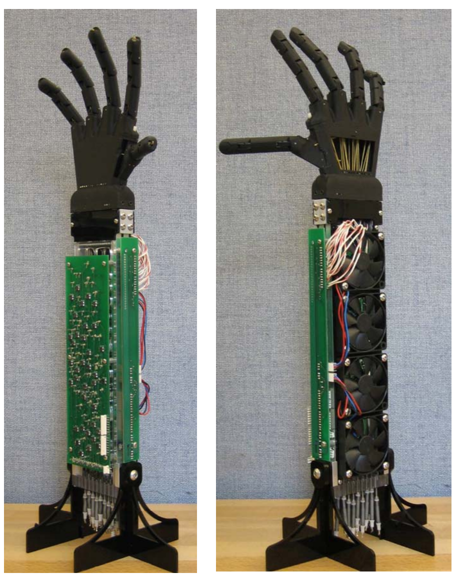

Fig. 2 Picture of the Robotic Hand

In this paper, we present the concept of using joule heated SBC, followed by an algorithms to generate C-segments from the given posture data. We apply the algorithm to a set of postures that are useful in daily life to the SBC hand. Finally, pictures of the robotic hand performing different postures are shown.

II. Concept of Joule-Heated Segmented Binary Control

Segmented Binary Control requires that each SMA actuator wire be divided into several segments. SBC has already been implemented with thermoelectric devices [6-8]. Although robust temperature control is possible with thermoelectric devices, they are slow, costly and quite inefficient. Joule heating would improve performance in each of these areas. Joule heating is accomplished by running a current directly through the SMA wire; a segmented design would entail that only a portion of the wire would experience said current. By applying a voltage difference between any two points on the wire, a current will be induced which would in turn heat up the selected segment.

C-segmentation can be implemented in two different ways, either by activating the coupled segments in series or in parallel. Isolation of multiple segments in each axis is much simpler in a parallel scheme, but it introduces more complications. Since joule-heating already requires relatively large currents (~3 amps) in order to activate the SMA with a reasonable response time, the simultaneous activation of multiple segments would require substantial currents. Furthermore, since the segments are of different lengths, which correspond to different resistances, each segment would have to be driven by different voltages in order to obtain equal currents, creating another level of complexity.

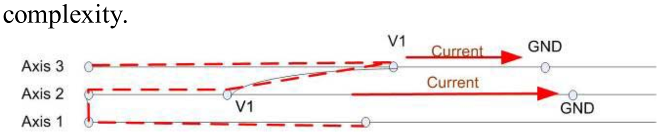

Fig. 3 Current flow in Joule Heated SMA Actuator Activation

The other option, driving the segments in series, makes it very difficult to isolate the different segments of each individual axis. While the activation of a single C-segment would entail the current following a very specific path, shown as the dashed line in Figure 3, simultaneous activation of multiple C-segments would result in multiple voltage differences within each wire. These voltage differences would serve to not only induce current in the desired paths but would also cause unwanted cross-currents through other C-segments (see Figure 3).

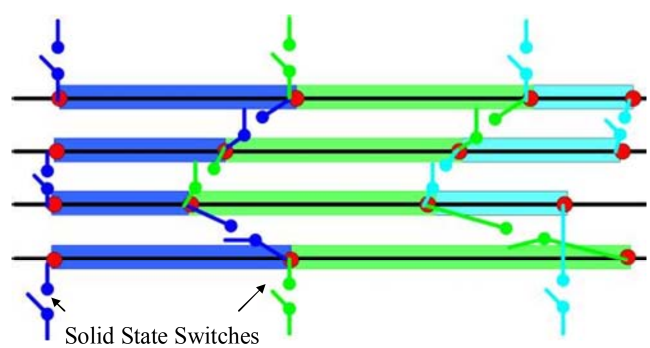

Fig. 4 Implementation of C-segment with Joule Heated SBC

The methodology used to isolate each C-segment has been coined Time Sharing PWM. It is implemented by first establishing a path between the electrical contacts of each segment of each axis of a given C-segment. The path is then connected using solid state switches. These switches are then only closed when the associated C-segment is activated. Thus the current is limited to only the desired path, resulting in the desired actuation.

PCB board with MOSFET switches, wiring scheme and holes for post connection is designed and fabricated to implement this concept.

III. C-SEGMENTATION ARCHITECTURE DESIGN ALGORITHM

In order to design the C-segmentation architecture, a set of target posture data is needed. This data was gathered through the use of a Cyberglove [12]. The gathered joint angle data is transformed into displacement data of the actuators that drive the robotic hand. Each posture of a robotic hand with *m* actuators can be represented as an *m*-dimensional vector, $\vec{y_x}$, with output displacements of each actuator as elements. As described in the introduction, each C-segment consists of a certain amount co-activated segments of each actuator axis. Therefore, C-segment can be represented as an *m*-dimensional vector, $\vec{w}$, where the i^{th} element represents the amount of i^{th} actuator axis that is to be included in the C-segment. When *r* C-segments are used, this C-segmentation architecture design can be represented as an *m* by *r* matrix, *W*. This matrix is analogous to a set of new coordinate axes, and any posture can be mapped to this new coordinate system. A coordinate that represents a single posture on this coordinate system is the encoding vector, $\vec{h}$, which represents the C-segments which are activated in order to reproduce the target posture. Therefore, the process of reproducing a posture using the C-segmentation architecture can be represented as a multiplication of the matrix W and encoding vector, $\vec{h}$.

If *n* desired postures are given, the data set of desired postures can be represented as an *m* by *n* matrix, *M,* where the column vectors are the actuator displacements required to produce the desired postures.

The encoding vectors will also form an *r* by *n* matrix, *H*, where the i^{th} column vector is the encodings needed to reproduce the i^{th} desired posture. The whole process of reproducing n different postures using *r* C-segments is now formulated into a multiplication of two matrices *W* and *H* to reproduce matrix M. Fig. 5 shows the matrices and its components.

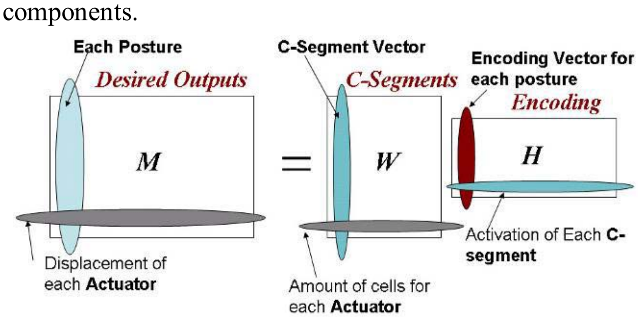

Fig. 5 Mathematical formulation of the C-segment design problem

The problem of finding the C-segmentation architecture design and the activations needed to reproduce the postures can now be formulated as a matrix decomposition problem, which is to find two matrices *W* and *H* that can closely reproduce matrix *M*.

If W and H matrices have no requirements, this problem can be solved by using principal component analysis; The actuators, however, can only be activated in one direction; the components of the C-segment matrix W must therefore be nonnegative. Another limitation is that in order to implement Segmented Binary Control, the components of encoding matrix H must be either 0 or 1.

The method of using Nonnegative Matrix Factorization (NMF) has been developed in [13]. NMF is a gradient descent algorithm which minimizes the Euclidean distance between the matrix M and the multiplication of matrix W and H. Although this method generates a reasonable solution, it often returns a solution at a local minimum, not at the optimal, due to the binary nature of the *H* matrix.

IV. EXPERIMENTAL RESULTS OF JOULE HEATED SBC

One issue which arises when using joule-heating in SBC is that there exists no simple way to achieve temperature feedback. This open loop approach makes it necessary to ascertain a method for consistently achieving desired displacement under a wide range of loading conditions. In this section, the feasibility of using joule heating to realize SBC is shown experimentally.

SBC requires that each segment be fully contracted when activated; the saturation characteristics of SMA make it a perfect actuator candidate. The energy necessary to ensure a full phase transition of the material must be first determined for proper control. In order to establish that the saturation characteristics were indeed salient, the SMA was subjected to varying power inputs and loading conditions. It was shown that there indeed exists a minimum energy input at which a repeatable actuator displacement is reached.

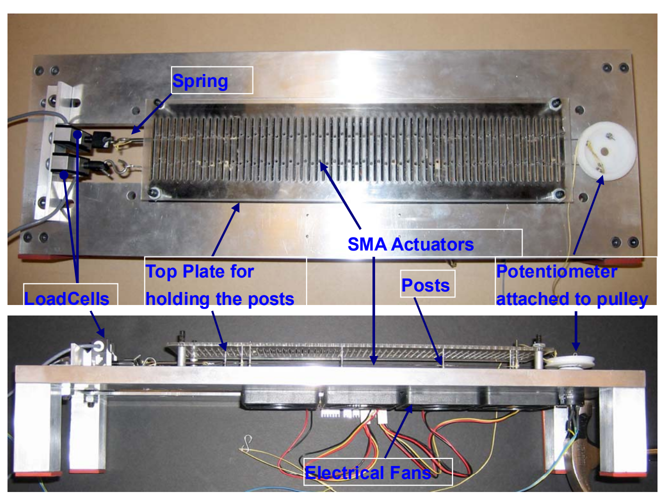

Fig. 6 Experimental Setup of Single Axis Joule-Heated Segmented Binary Control of SMA actuator

Fig. 6 shows the top and side view of the experimental setup. It is equipped with load cells to measure the applied force and a potentiometer connected to a pulley to measure the displacement of the actuator. The apparatus has two SMA actuator wires set up in an antagonistic configuration. One SMA actuator is connected directly to a load cell and to the pulley, while the other is connected to a spring which is connected to a different load cell and to the pulley as well. A current controller with precise ON time control is used to control the input power to the SMA wire.

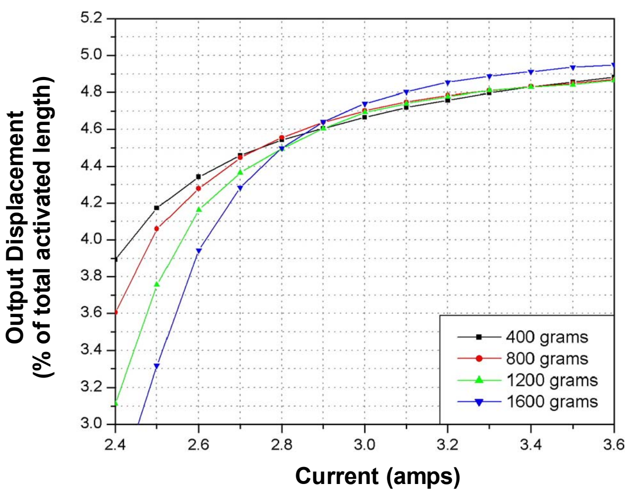

Fig. 7 Experimental result of activation with different currents under different loading conditions

In order to find the operating conditions as well as to verify the joule heated SBC, 9 inches of SMA wire was activated for 1 second with current inputs from 2.4 amps to 3.6 amps. Fig. 77 shows the results of this experiment. As shown in the graphs, the output displacements were not repeatable when currents of 2.7 amps or below were used. However, for currents 2.8 amps and above, the output displacements were repeatable throughout the different loading conditions. This result shows that the use of a set current amplitude for driving the SMA actuator will result in equal displacement regardless of load conditions and that SBC can be implemented with joule heating.

V. Hardware Implementation

A robotic hand was designed specifically for the implementation of segmented binary control of thermally activated SMA. Other considerations in the design included the minimization of weight and size, with an overall focus on simplicity.

It was decided that the best approach for cooling given the above parameters would be simple forced convection. The efficiency of the cooling, however, is limited by the ease of airflow. The implementation of SBC requires several electrical connections per axis. Since a human hand has in excess of 16 controlled D.O.F., multiple electrical connections in multiple axes creates the need for an unconventional method of establishing electrical contact.

Figure 8 illustrates a paradigm in which the electrical contact is made via metal posts which run perpendicular to the actuator wires. In this setup, the majority of the space in the forearm is empty, allowing for almost uninterrupted airflow from the fans to the SMA wires.

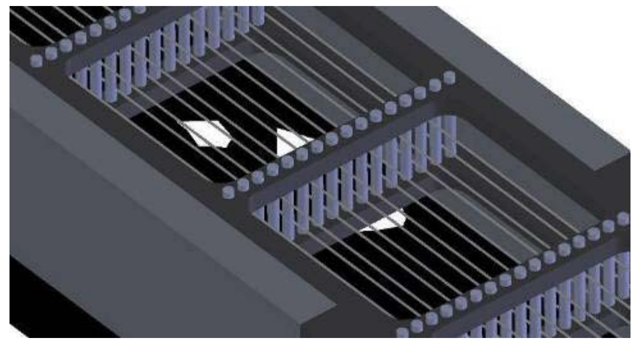

Fig. 8: Segments of SMA contacting perpendicular pins which can be connected to a circuit board.

Using this electrical contact scheme, however, makes it necessary to maintain constant tension in the SMA wires; slack could lead to loss of contact, or even short circuiting and the unintentional activation of other axes. This presents quite the problem as SMA is a unilateral actuator being implemented in an antagonistic arrangement. As can be seen by figure 9, the total length of the paired actuators changes when one of the axes is activated, which would in turn cause slack.

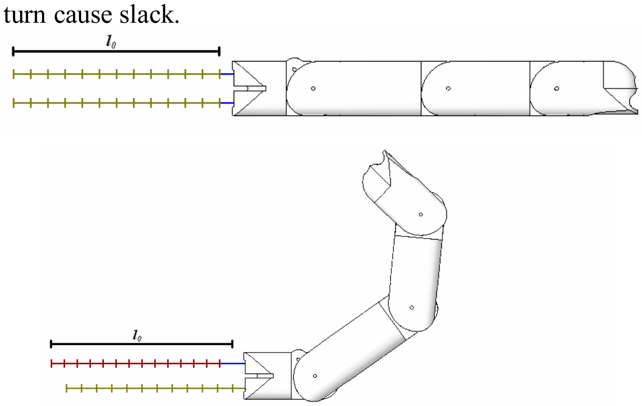

Fig. 9(a) Relaxed finger with unactivated actuators at natural length (l_0). (b) Bent finger with flexor axis activated

With this in mind, it becomes necessary to either have one axis in each pair continually activated, or to introduce compliance. It is simply impractical to maintain tension by maintaining one axis constantly activated; if tension is lost, the electrical connection will also be lost which will in turn prevent any actuation at all. The other option, compliance, also places severe limitations on performance. Excessive compliance limits the efficacy of the attached actuator while insufficient compliance limits the force exerted in grasping.

There exists, however, a solution to this dilemma. A concept known as *Travel-Limited Compliance* can provide the necessary compliance in situations which require it while providing virtually no compliance in situations in which it would be detrimental. Figure 10 illustrates one approach to the implementation of this concept.

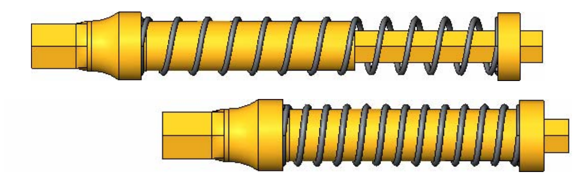

Fig. 60 (a) Relaxed compression spring (b)Compression spring at travel limit

In order for this scheme to work, it is only necessary to have one axis of each antagonistic pair fitted with a travel-limited spring. The most logical setup would be to fit the extensor axis of each finger with the travel-limited compliance. The lengths of each actuator must then be calibrated such that the device is at full travel when the finger is fully flexed.

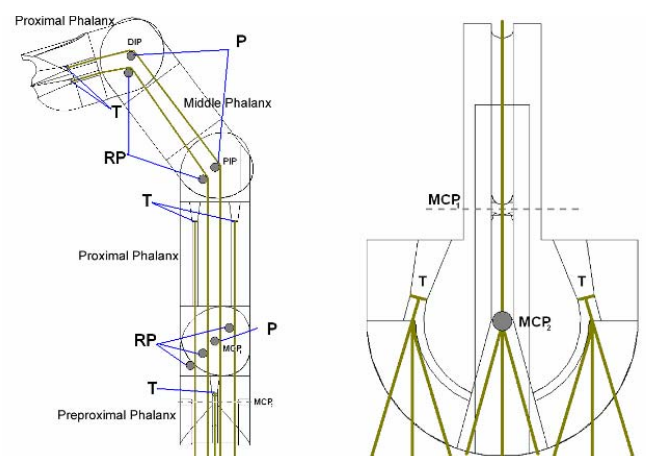

Fig. 71 (a) Orthogonal view of tendon routing (b) Tendon routing of MCP segment.

This allows for several things: It creates a neutral position of the fingers fully extended in the case of neither axis being activated; it absorbs any slack which may be present from under-activation with sufficient compliance so as to not impede flexion; and it allows for a pullback utilizing the full force that the actuators are capable of exerting.

Each finger was designed to mimic the functionality of the human hand, consisting of three main segments, six tendons and four degrees of freedom. Figure 11 illustrates the tendon arrangement.

Two of the tendons travel the entire length of the finger and terminate in the distal phalanx segment; two terminate in the proximal phalanx segment, and two terminate in the preproximal phalanx segment. As can be seen in figure 12(b), all tendons associated with flexion and extension pass through the center of the preproximal phalanx. This configuration allows for no coupling between the abduction/adduction and flexion/extension motions.

There is coupling, however, between the tendons that terminate in the distal phalanx and in the proximal phalanx. While this does mimic the anatomy of the human hand, it introduces a new source of slack in the actuators. As such, it has proven itself necessary to include travel-limited compliance in the flexor axes as well. In order to maintain fidelity of position control, the springs for these limiters were chosen with a significantly lower stiffness than those associated with their antagonistic counterparts. As such, they remain travel limited in all cases except when axes to which their motion is coupled are activated.

This design allows for a robust position control while maintaining electrical contacts.

VI. Robotic Hand with C-Segmentation Architecture

Sixteen different hand postures based on everyday life have been gathered and used to generate the C-segmentation design. The process began by finding data on 16 hand postures using the cyberglove, as shown in Fig. 9. The angles measured by cyberglove had to be transformed since they correspond to the angles of joints in a human hand which has slightly different geometry than the robotic hand.

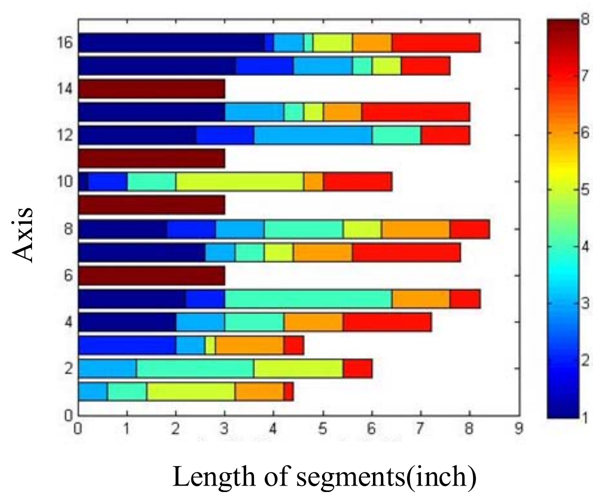

Fig. 12 C-segmentation Architecture Design

Using this C-segmentation design, all sixteen hand postures can be reproduced. Fig. 9 shows pictures of the actual grasps, the robotic hand posture from the captured data, and recreated robotic hand posture using the C-segmentation. The error in the grasps varies from 0 to 30 degrees. The cause of error is not just due to the actuator C-segmentation design. Since the robotic hand is underactuated, the hand postures captured using the cyberglove cannot be perfectly reproduced. Therefore, the error shown in each figure should be considered a conservative value of error, not an exact value.

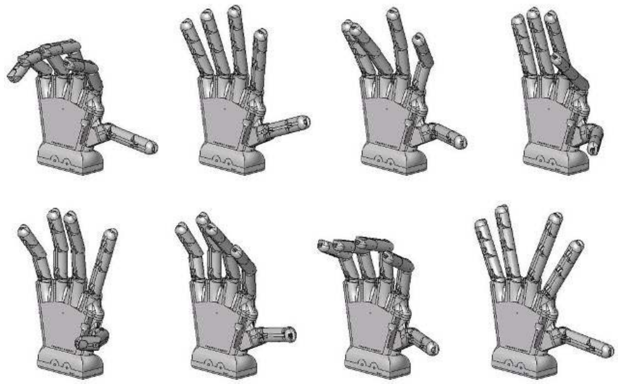

Fig. 8 Figure of eight C-segment Postures. These primitive postures are used to create the postures needed.

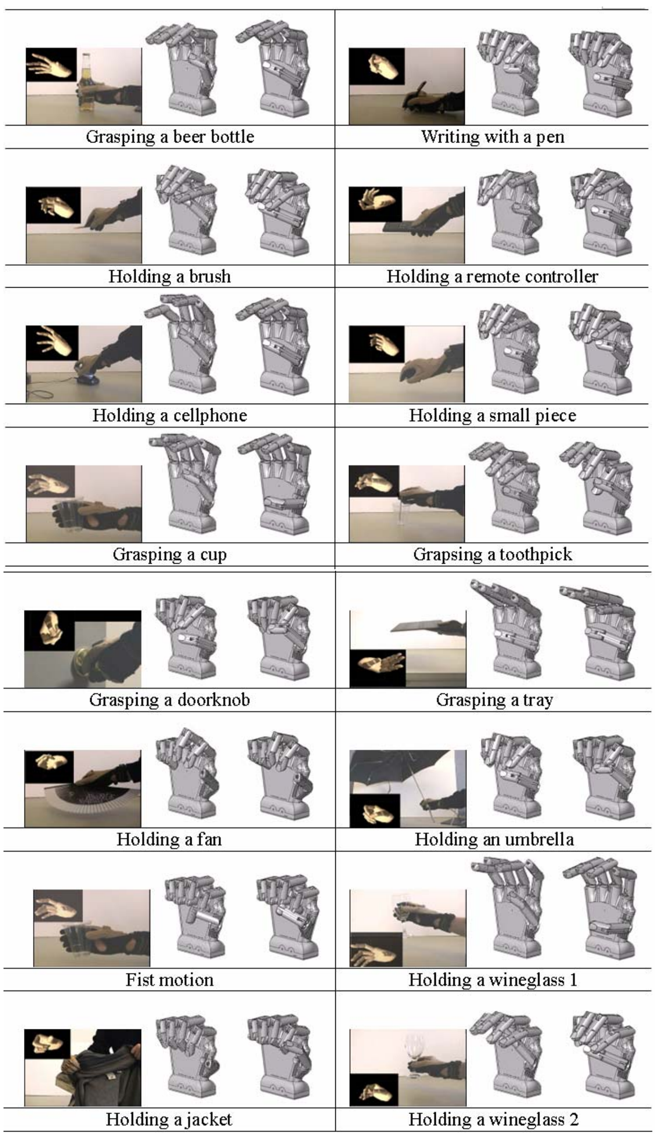

Fig. 9 Comparison of captured grasps and reproduced grasps

VII. CONCLUSION

A lightweight robotic hand using a joule heated Segmented Binary Control has been developed. A concept of synergy that reduces the dimensionality of the control signals, known as C-segmentation, is presented with an algorithm that enables us to design the C-segmentation automatically when a set of desired postures are given. The robotic hand has 16 controlled DOF and 32 independent SMA axes and the total weight of the robotic hand system was less than 800 grams. 16 different grasping postures were successfully recreated by using only 8 C-segments. Due to the error in the postures, compliant fingertips are needed to perform actual grasping tasks. Theoretically, 256 different postures can be generated with 8 C-segments; A group of co-activated, binary controlled segments. Therefore, a robotic hand with simple control can perform various tasks needed for a robotic hand.

ACKNOWLEDGMENT

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