Proceedings of the 2009 IEEE
International Conference on Robotics and Biomimetics
December 19 -23, 2009, Guilin, China

Omegabot : Biomimetic Inchworm Robot Using SMA Coil Actuator and Smart Composite Microstructures (SCM)

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Abstract— **Many researchers have developed various robots with novel gaits that can travel on rough terrain where conventional vehicles or other robots cannot. Many of these robots are bio-inspired since there is lots of amazing locomotions in nature that enable movement through various obstacles. This paper presents a robot based on the motion of *ascotis selenaria*, a type of inchworm with a locomotion that has an omega shape bending motion in between the extension motions. This type of inchworm can travel approximately its body length per stroke on a rough surfaces, leaf edges and branches of trees. The robot is built with smart composite microstructures, a fabrication method that uses laser micromachining to cut composites and assemble them into micro structures. The robot is actuated with a single shape memory alloy coil actuator. This robot can be used for search and rescue or gathering useful information in an area where only small scale robots can penetrate.**

I. INTRODUCTION

THIS paper describes the design and the fabrication of an inchworm robot based on the motion of *ascotis selenaria*.

A few robots inspired by worm-like motions have been developed that propel themselves in various types of environments [1]-[3].

There are two types of worm-like motions. One is the peristalsis type (e.g. earthworms, sea cucumbers, caterpillars, snails). A representative worm of peristalsis type is an earthworm. An earthworm is composed of many segments, and it can expand and contract its body with circumferential and longitudinal muscles [4]. These segments create a traveling wave by sequential activation. The other is an inchworm-type motion. An inchworm moves forward by alternating two kinds of stroke motions: longitudinal extension motion and Omega (Ω) shape bending motion [5]. Fig. 1 shows the difference of motions between a peristaltic worm and an inchworm.

In this paper, we present a robot that mimic the Omega (Ω) shape bending motion of *ascotis selenarena*. The Omega (Ω) motion is a simple way of crawling on a rough terrain and climbing on a wall. It doesn't generate sequential motions like earthworms do. It consists of multiple segments where the first and the last segments touch the ground, while the segments at the middle create an omega shape when the actuator is activated and extends when deactivated. Combined with a silicon polymers attached at the outer tip of the first segment and the inner tip of the last segment, repetitive generations of this omega shape creates a forward movement. The middle part of the body does not need to touch the ground and the robot moves forward by alternating between the two motions.

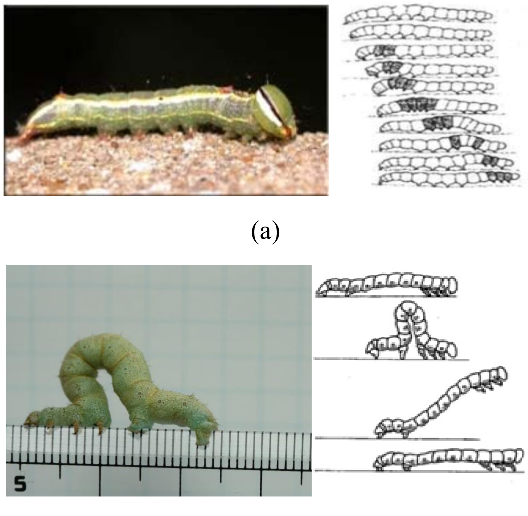

Fig. 1. Different motions between peristaltic worm's and inchworm's. (a) sequential motion of a multi-segment normal caterpillar, (b) Omega(Ω) motion of an inchworm.

Inchworms that show Omega (Ω) motion move approximately one body length per stroke. Omega motion can be implemented with a simple control and actuation architecture and is suitable for miniaturization and passive adaptation to the environment.

The robot is fabricated using smart composite microstructures (SCM) and actuated using SMA coil spring actuators [6, 7]. SMA coil spring actuators and SCM have advantages in building meso-scale robots. SMA has high energy density and unique two-phase (martensite /austenite) property. Using these characteristics, SMA has actuated robotic hands [8], several robotic fish fins [7, 9], crawling micro robot [1, 3]. SCM is used to build micro linkage structures fabricated from 2D pattern cutting of composites using micro laser machining. It doesn't use metal based pins and link joints that cause large friction loss at micro scale. Flexible polymer films and composites replace pins and metal links. 3D micro robot structures, e.g. micro flying insect robot [6], are made from 2D pattern.

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978-1-4244-4775-6/09/$25.00

The rest of the paper is as followed. Section II describes the design of the robot based on SCM. Crawling motion is described followed by a 2-dimensional turning motion. Section III shows an analysis of the bending of the flexure joints. Section IV describes the fabrication of the robot and section V shows the results.

II. DESIGN

A. Crawling Structure Design

As described earlier, inchworms can crawl on various terrains using a simple Omega motion. This motion is realized with multiple rigid segments connected with flexible joints. An SMA coil spring actuator is attached to the structure in a way that makes the structure bend and form an Omega shape when activated. Directional friction is used to allow the robot to move forward, but not backward.

Figure. 2 shows the schematic diagram of the Inchworm robot that can generate the Omega motion based on a SCM structure and a SMA coil actuator. White squares are glass fiber composites. Those are used as rigid part of linkages. Black connecting lines are Kapton films that are used as a flexure joint. Electric circuit for wiring of SMA coil actuators is fabricated on the copper laminated Kapton film. As shown in the diagram, a single SMA coil actuator exists, composed of three serially connected coils. The line of SMA passes through particular holes in composites as shown in the diagram. Omega motion can be generated by this arrangement of the actuator.

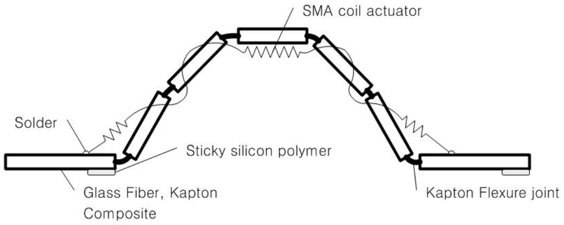


Fig. 2. Schematic diagram of Inchworm Robot.

As seen in the diagram, sticky silicon polymers are attached asymmetrically at the bottom of the first and the last segments which touch the ground. On the first segment, the polymer is attached at the outer tip, while on the last segment it is attached at the inner tip. The mechanism of creating a forward movement using this structure is shown in Figure. 3.

The crawling mechanism has two steps. The first is an actuator contraction as shown in Fig. 3(a). The inner tip of the first and the last segment touch the ground. The polymer attached at the inner tip of the first segment generates friction force that fixes the first segment while the last segment slips forward. The second is an actuator release as shown in Fig. 3(b). A SMA coil is extended and the outer tips of the first and the last segment touch the ground. Then the sticky polymer at the last segment has friction while the first segment slips forward. The robot moves forward by alternating between those two steps.

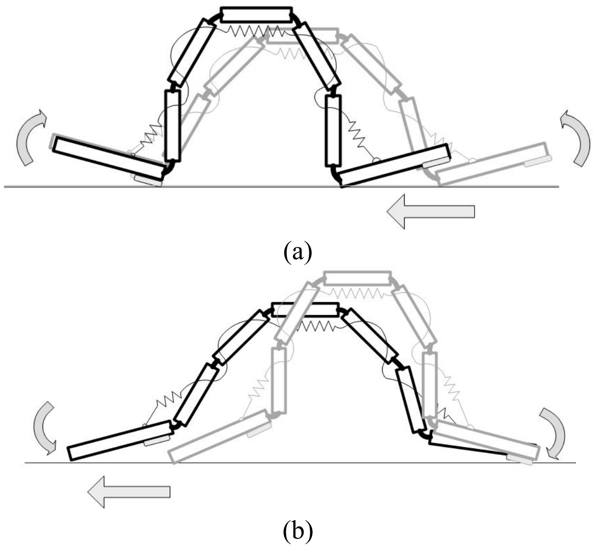


Fig. 3. The mechanism of crawling (a) actuator contraction step (b) actuator release step

B. 2 Dimensional Bending Structure Design

The SCM structure is based on a 2D pattern; hence it is hard to create a multi degree joint similar to universal joints. For the inchworm robot to turn while crawling forward, a two dimensional bending motion is required. Both bending motion are orthogonal to the direction of the forward movement. Pitch axis bending generates a forward movement while the yaw axis bending generates a turning motion. We propose a structure similar to origami that enables turning motion.

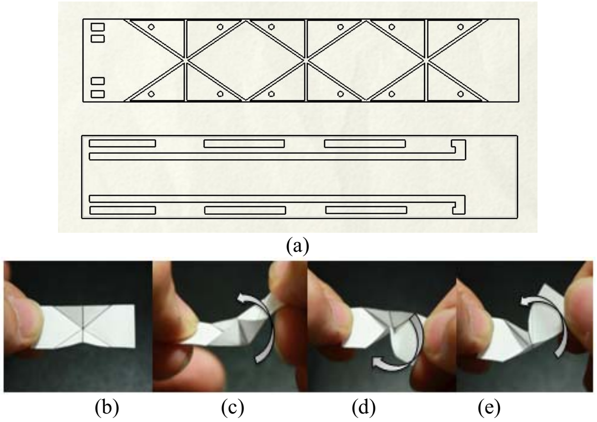


Fig. 4. (a)2D pattern design of Universal joint for SCM (b)Paper Origami trial version of (a). Pitch bending motion (c), Yaw bending motion (d), (e).

Figure. 4(a) shows the 2D pattern of the SCM joint structure that can create two degree of freedom joint when folded. Lower pictures of Fig. 4 are a series of pictures that demonstrate the two dimensional bending motion of the structure. The small circles in triangles are the soldering spot to connect actuators. The lower figure of (a) is the circuit pattern. It connects the circle holes to two actuation lines. Two actuation lines are actuated separately. When both lines are actuated, the structure is bent forward as seen in Fig. 4(c). When one of those lines is actuated, the structure is bent to one side where the actuation is generated as seen in Fig. 4(d)(e). By actuating two actuator lines separately, this structure can generate a crawling motion and a turning motion.

C. Actuator Design

The SMA coil actuator generates force when heated above phase transformation temperature. SMA phase transformation from Martensite to Austenite occurs at the phase transition temperature of 70℃.

Diameter of the wire (d) is 100um, and the coil spring diameter (D) is 380um. The spring index C is 3.8.

$$\delta = \frac{8PD^3n}{Gd^4} \tag{1}$$

$$k = \frac{Gd^4}{8D^3n} \tag{2}$$

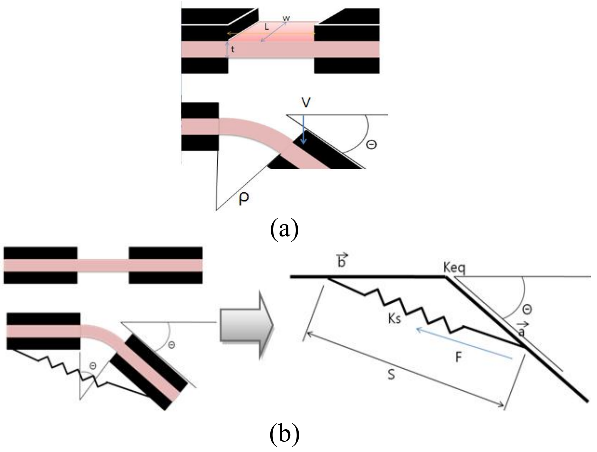
According to the formulas (1) and (2), the coil spring constant at the austenite phase when the coil is actuated is about 200N/m (Where shear modulus (G) of Ni-Ti at austenite is 23000Mpa, the number of active coil (n) is 60) [10]. In order to create the Omega motion using a single actuator, serially connected SMA coil actuator is designed as seen in Fig. 2. The coil length and location of soldering is determined based on a joint modeling data and several experiments.

III. FLEXURE JOINT ANALYSIS

The flexure joint modeling is required to determine the proper SMA coil actuators, the thickness of flexure joints, and the values of several design parameters. The flexure joints have stiffness. By estimating the stiffness of the joints, the torque and the bending angle can be computed when the actuators make force.

A. Flexure joint modeling

the joint of the smart composite microstructures (SCM) is composed of a flexible sheet part and a rigid composite part. The joint is assumed to be a thin film flexure as shown in Figure. 5(a). Joint stiffness and moments are derived from linearized beam bending formulas, Where v is a vertical length of a bending, θ is a bending angle, ρ is a radius of curvature, M is moment, E is young's modulus, I is area moment of inertia, L is width, and S is a length of coil actuator.



(a)

(b)

Fig. 5. Schematic diagram of flexure joint. (a) Flexure part (b) Total joint.

$$\frac{dv}{dx} = \sin\theta \tag{3}$$

$$dx = \rho d\theta \tag{4}$$

$$\frac{1}{\rho} = \frac{d^2v}{dx^2} \tag{5}$$

$$\frac{1}{\rho} = \frac{M}{EI}\left(I = \frac{wt^3}{12}\right) \tag{6}$$

$$M(Flexure) = \frac{EI}{L}\theta \tag{7}$$

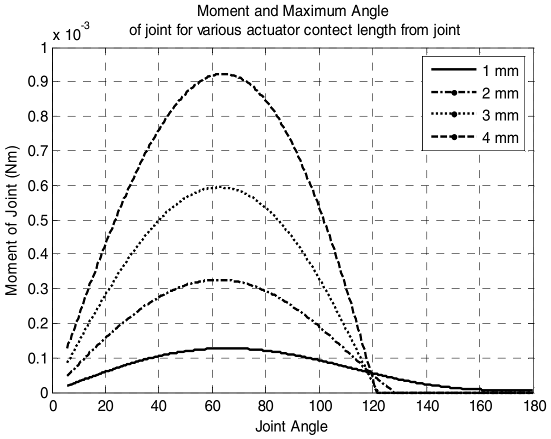


Fig. 6. Graph of relationship between joint angle and total joint moment.

Fig. 5 (b) shows a schematic diagram of a combination of a flexure joint and a SMA coil actuator. K_s is the SMA spring coefficient, where K_s is computed as 200N/m.

Total moments are,

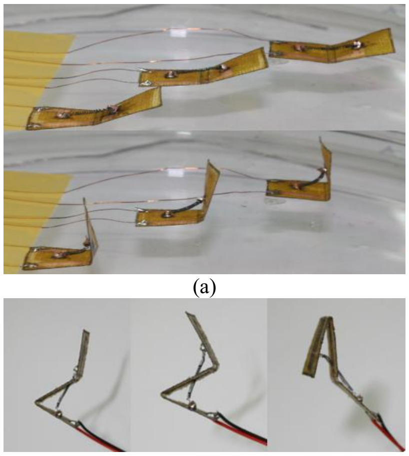
$$M_{(SMA)} = \vec{a} \times \vec{F} \quad \left(\vec{F} = Ks \bullet \Delta S\right) \tag{8}$$

$$M_{(total)} = M_{(SMA)} + M_{(flexure)} \tag{9}$$

where a, b is vector of the actuator soldering spot, F is the force generated by the coil actuator.

Maximum torque and bending angle are related to the soldering point (vector 'a') where the SMA coil actuator is soldered. Figure. 6 shows the graph of the moments on the joint. Four different graphs are plotted for different length of the distance vector 'a'. Each graph shows the moment as the bending angle changes from 0 to 180° after the actuator is activated. As the joint bending angle increases, the moment increases because the moment arm becomes larger. But the stiffness of the joint increases as the bending angle increases, and the actuator force decreases. Therefore the moment reaches the maximum value and starts dropping at a certain point. The joint angle, when the moment becomes zero, is the equilibrium points. As seen in the figure, the maximum moments and the equilibrium points are different for different lengths of vector 'a'. It means the joint angle and torque is controlled by the actuator soldering point.

B. Flexure joint experiments using modeling data


(a)

(b)

Fig. 7. Experiment result of a flexure joint (a)C-type block equilibrium angle change, (b)S-type block equilibrium angle change for the actuator soldering point length from flexure joint

Modeling provides a tendency of joint behavior for various lengths of actuator soldering point. Using the result we can control the maximum bending angle.

Basically Omega motion is composed of two bending blocks C-type and S-type [7]. Combinations of C-type and S-type bending motions can generate travel waves and, snake like motion, etc. The experiments are performed to make two bending types and control bending angle by soldering point. Result is shown in Figure. 7.

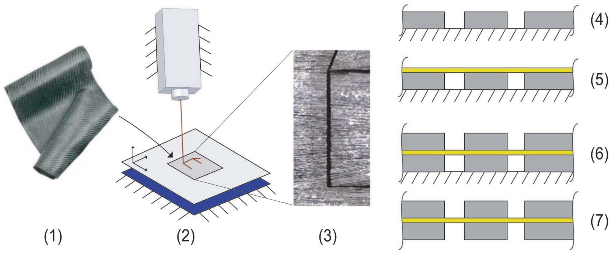
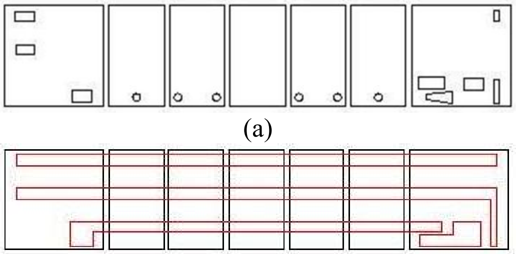
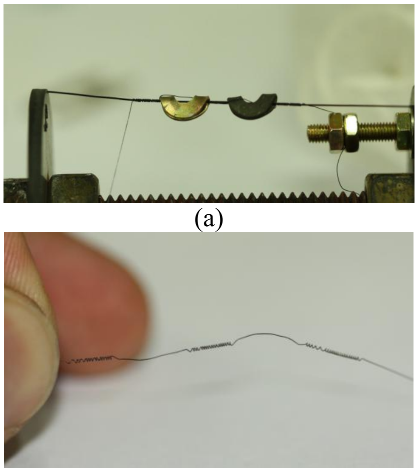


Fig. 8. Overview of the laser micromachining step of the SCM process. Composite prepreg(1) and thin-film polymer laminae are laser cut(2) to desired platform geometries(3). These laminae are then aligned, stacked(5-6), and cured to form the spine segments(7) [7].


(a)

(b)

Fig. 9. (a)2D pattern design of Inchworm robot platform for SCM (b)Flexible circuit pattern for laser machining.


(a)

(b)

Fig. 10. (a)SMA wire is wound on larger wire to make the shape that fits on the segmented structure (b)SMA coil actuator made by annealing.

IV. FABRICATION

A. Flexure Structure Fabrication

SCM is fabricated by following procedure as seen in fig. 8. Glass fiber prepreg is used as a rigid part link. Two single layer glass fiber laminae are joined orthogonally, and cut with a laser, and flexible part is made by copper laminated Kapton (Polyimide) film. Copper laminated film is used because it can be used as a flexible circuit. Figure. 9 shows the 2D pattern design of the glass fiber prepreg and copper laminated Kapton film.

The circular holes shown in Fig. 9(a) are where the SMA actuator passes through to the opposite side, and the square holes are where the electric devices and SMA actuators are soldered. The red line in Fig. 9(b) is a copper film remaining on the Kapton film. It is used as a circuit.

B. Actuator Fabrication

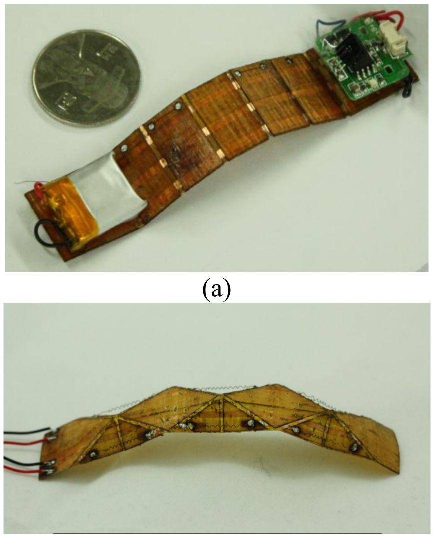
The SMA coil spring actuator is made by thermal mechanical treatments of SMA wire. In order to change the shape of SMA wire, it needs to be annealed at high temperature between 500~600 Celsius degree. After annealing, austenite phase shape of the SMA changes to a desired shape [7].

First, SMA wire is wound on a diameter of 380um, as the spring is customized by using some parts like Figure. 10(a). 100um SMA wire is used to make a coil. We put two washers in the middle of the coil to make a linear part of the actuator fit on the segmented structure.

It is annealed at 550 Celsius degree in the furnace.

C. Circuit Fabrication

Flexible circuit is made of a copper laminated Kapton film. First, a masking film like Kapton tape covers the whole copper area of copper laminated Kapton. The masking film is cut using laser machining and make circuit pattern on the copper film. Extra Kapton tape is removed except for the circuit patterns. The copper area is etched by Ferric chloride solution. After etching, only masked copper part remained at Kapton film.


(a)

(b)

Fig. 11. Prototypes of Inchworm robot (a), Universal joint of SCM (b)

D. *Assembly*

Power, wireless control receiver is embedded on the inchworm robot as shown in Figure. 11(a). Battery is a 3.7V Li-ion battery and has an electric power of 40mAh. Wireless receiver is based on an IR sensor. IR remote controller sends the signal.

Fig. 11(b) is a prototype of a SCM universal joint. SMA coil actuators are soldered on each joint of the structure designed by 2D origami pattern. After assembly it has pre-bending to avoid singularity of joint. SMA coil actuator generates linear actuation. If the joint is parallel to the actuator, singularity occurs. But singularity problem can probably be solved by changing the geometry of the structure.

V. RESULTS

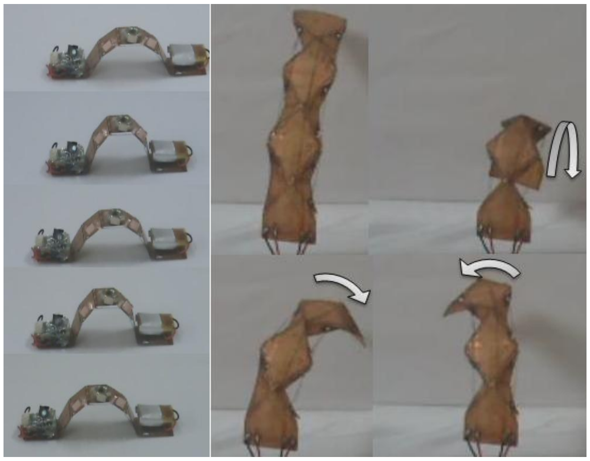

(a) (b)

Fig. 12. Motion of Inchworm robot crawling (a), Two degree of freedom bending motion of SCM universal joint (b)

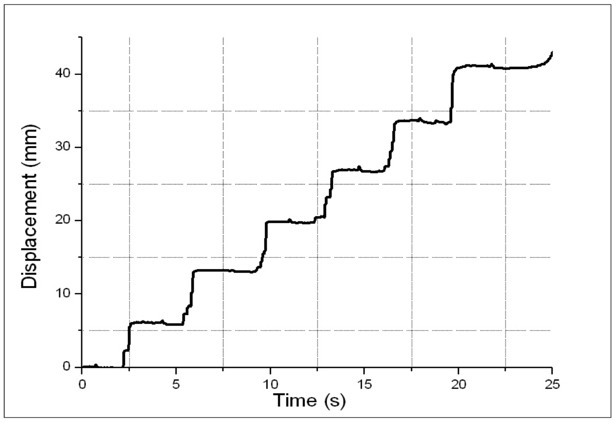


Fig. 13. The displacement graph of Omegabot for crawling motion

The inchworm robot, which generates an Omega motion for crawling, and an Universal joint structure are tested. The inchworm robot is controlled by IR remote controller manually. The SCM universal joint prototype is tested by applying current to each side actuator.

Inchworm crawling robot has battery of 3.7V, 40mAh. The SMA coil actuator consumes 200mA current to activate. By computing the energy consumption, the robot can operate 1440 cycles of Omega motion stroke. According to SMA coil actuator characteristic, 1Hz operation period can be achieved. The maximum velocity of the robot is 5mm/s. Figure. 12(a) shows the video capture of the crawling motion. Figure. 13 is the displacement graph of Omegabot plotting with video analysis program. As seen in the picture, the robot travels a distance of 5mm per stroke.

Two degree of freedom motion of SCM universal joint can be seen at Fig. 12(b). It has three joints connected serially. SMA coil actuators are attached to each side of the joint and can be actuated separately. To perform a turning motion, only one side actuator is activated like the lower part of Fig. 12(b),and to bend forward, both side actuators should be activated. Using this control mechanism, two degree of freedom bending joint is realized.

VI. CONCLUSION

This is the first step to establish inchworm like robot which can crawl on a various terrains where conventional robots cannot travel. We chose the inchworm as the model. An inchworm has the simple crawling motion which we have named Omega motion. It does not need the sequential control but a single stroke generation. Because of this simple mechanism, it can be accomplished by the simple structure and control method.

The Smart Composite Microstructures (SCM) make it possible to build a micro scale linkage structure.

There is a lot of design parameters in the SCM 2D-pattern design. For example, SMA coil actuators solder position can change the bending angle of a flexure joint, and various geometric parameters exist on 2D pattern design of SCM Universal joint like e.g. angle of each triangle shape and length of square. These parameters affect the final performance of the robot and energy consumption.

ACKNOWLEDGMENT

This work was supported by Research Settlement Fund for the new faculty of SNU, Basic Science Research Program through the National Research Foundation of Korea(**NRF**) funded by the Ministry of Education, Science and Technology (0420-20090027)

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