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Towards a Bio-mimetic Flytrap Robot Based on a Snap-Through Mechanism

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***Abstract*—This paper presents a bio-mimetic flytrap robot based on the Venus flytrap, which has rapid snap-through motion. The robot employs a bi-stable unsymmetrically laminated carbon fiber reinforced prepreg (CFRP) structure, which has a bi-stable mechanism that is similar to the Venus flytrap's passive elastic mechanism. By embedding shape memory alloy springs, large deformation is induced and bi-stable structure can be triggered to snap through. The robot's working performance shows that the leaves close in about 100ms, and this time for closure is almost the same as that of the Venus flytrap. This concept of the flytrap robot can be applied to rapid grippers of various sizes.**

I. INTRODUCTION

One of the fastest motions in the plant world is that of the Venus flytrap (*Dionaea muscipula*), which can close its leaves in about 100ms. Generally, most plants cannot move as rapidly as the flytrap. They move 1cm or less per day. Aristotle even defined plants as things that do not move, which makes the flytrap's rapid movement a very curious and interesting phenomenon.

Even though this fast motion of the flytrap is significant from the viewpoint of active rapid movement in comparison with general stationary plants, the principle of the rapid closure has not been explained very well for a long time. Recently, Mahadevan discovered some part of the secret of that motion [1]. According to his research, the Venus flytrap mainly uses a snap-buckling instability in a doubly-curved leaf and has two principles of trap snapping. One is an active biochemical process and the other is a passive elastic process. The active biochemical process is explained as a process that is caused by action potential, but it is still not clearly verified. The passive elastic process results from the characteristic of special leaves with strain fields that cause bi-stability. This operating principle will be explained in more detail in the next section.

The snap-through motion of the Venus flytrap's leaves is similar to the shape transition process of a bi-stable laminated composite structure. The principle of bi-stable composite structures has been examined in many studies. Hyer has summarized bi-stability in research on unsymmetric laminates and observed a cylindrical curvature in the structures [2]-[4]. Using a prestressed hot plate machine, Weaver also investigated bi-stable laminates that are prestressed and unsymmetric [5]. In the prestress process, the carbon fiber prepreg is elongated using clamps, pressed with a hot plate, and released at room temperature. In addition, several kinds of analytical models are developed for predicting the shape of bi-stable structures. Hyer conducted a simple force-controlled experiment that is used to measure the snap-through moment and the characteristics of the change in configuration, by way of strains [6]. Cho et al. investigated the slippage effects on the bi-stable curvatures of unsymmetric composite laminates after curing [7]. Kebadze investigated a cylindrical shell that has two stable configurations, due to a particular distribution of the residual stresses that are induced by plastic bending [8]. Guest investigated various bi-stable shapes in thin cylindrical shell structures using a simple two-parameter model [9].

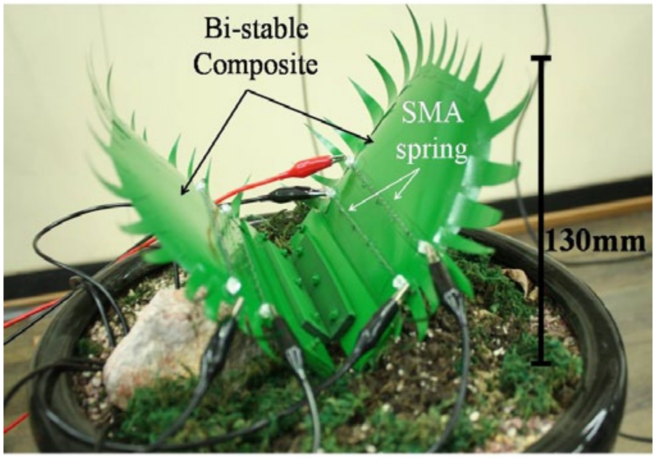

Fig. 1. Bio-mimetic flytrap robot with SMA spring actuator

Also, many researchers tried to apply bi-stable structures for morphing or deploying and embedded various actuators for activating structures [10]-[12]. These structural morphing concepts can exploit structures that have multi-stable configurations and expend energy only to change from one configuration to another rather than continuously consuming energy to maintain the changed configuration [13].

Hyer developed a theory and designed experiments to study the concept using shape memory alloy (SMA) wires to trigger the snap-through of unsymmetric composite laminates [10]. Birman also used SMA wire for supporting composite plates [11]. Although SMA wire actuators can be attached to the bi-stable CFRP composites easily, the SMA wire displacement is limited to 3-4% and can only be applied to

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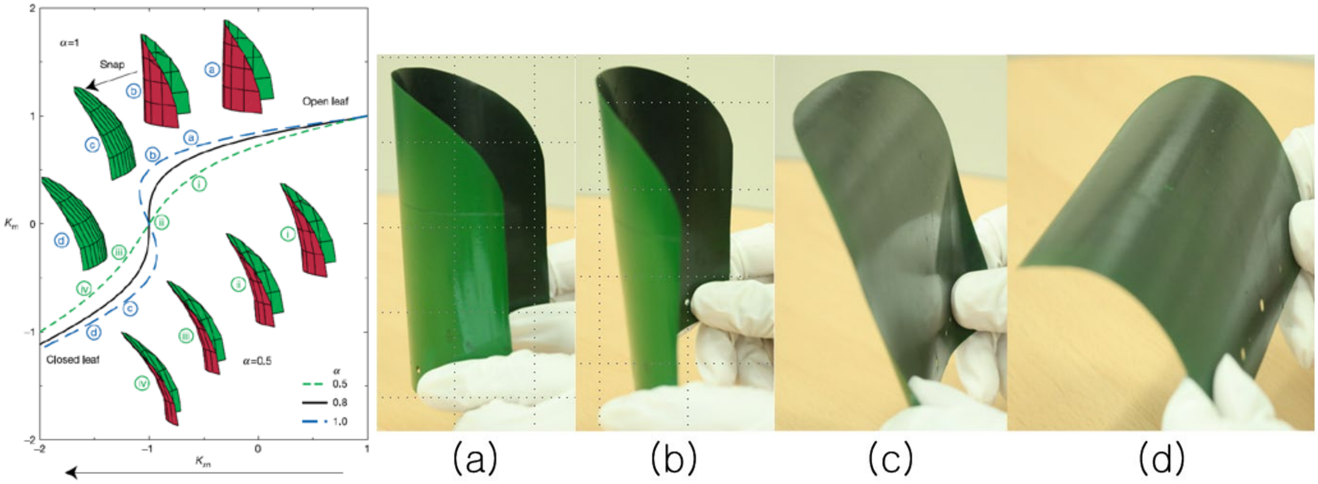


Fig. 2. The flytrap's smooth-snapping transition in a leaf-closure diagram [1] (far left). (a)-(d): the CFRP composite snap-through process sequence.

morphing structures with small curvature.

Bowen investigated unsymmetrical carbon fiber/epoxy composites with bonded piezoelectric actuators as a means to shape or morph composite structures [12].

Plants with unique characteristics have been studied by researchers who seek to recreate their unique features to solve engineering problems or these features in real-world contexts. Velcro was inspired by the burdock's ability to attach easily [14]; also, super-hydrophobic surfaces are being developed based on the ability of the lotus to repel water drops [15].

In this paper, we try to mimic the Venus flytrap's unique way of creating a rapid gripping motion. We use a carbon fiber reinforced prepreg (CFRP) composite bi-stable structure and a SMA spring actuator. The SMA spring actuator has large displacements that can overcome the limits of shape deformation noted in previous studies and be applied in bi-stable structures that embed actuators [16].

In the following sections, the principle of flytrap snapping based on Mahadevan's research is summarized [1], the mechanism of bi-stable composite structures is explained. Our flytrap design and manufacturing process are described. Finally, we present a working prototype shown in Fig. 1 and discuss the results regarding its performance.

II. THE PRINCIPLE OF THE FLYTRAP'S RAPID MOTION

From a common-sense point of view, plants do not move quickly. However, some plants move. For example, the bending of tentacles in Drosera, the movement of stamens in Berberis and the bending of a mimosa leaf [17]. The most frequently proposed explanations for the mechanism of this rapid movement are based on the cellular mechanism, which includes an irreversible, acid-induced wall loosening [18], and a rapid loss of turgor pressure in motor cells [19]. Hodick pointed out that it is not clear that these existing explanations about the mechanism of rapid motion are adequate [19]-[20]. He suggested a different idea, namely, that the mechanism of rapid motion is related to elastic deformations. Using high-speed video imaging, non-invasive microscopic techniques and a simple theoretical model, Mahadevan proved that this hypothesis is correct, i.e., that the fast closure of the trap results from instability in snap buckling, the onset of which is controlled actively by the plant.

In the far-left diagram in Fig. 2, Mahadevan illustrated the smooth-snapping transition in the closure of the flytrap's leaf [1]. For this doubly-curved leaf, the dimensionless natural curvature of the leaf in the x-direction, K_{xn}, decreases from positive to negative; the leaf changes its mean curvature, K_m. Thus, the bending of the leaf causes the mid-plane to be stretched.

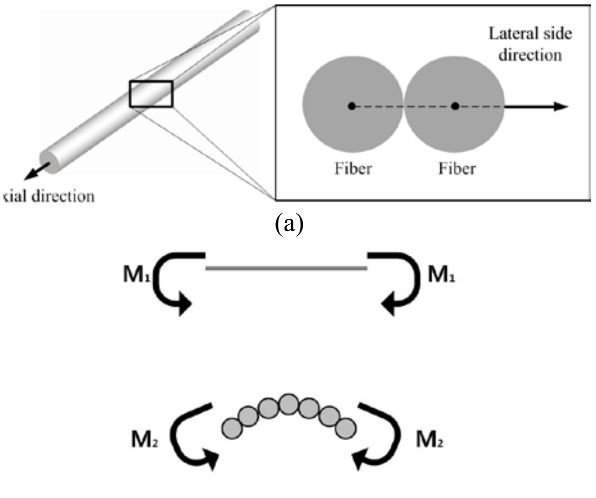
In addition, he verified that a dimensionless geometrical coupling parameter, α, characterizes the relative energy penalty of bending-to-stretching deformations, where α is defined as:

$$\alpha = L^4 \kappa^2 / h^2 . \tag{1}$$

in terms of the leaf thickness h, the leaf size L, and the observed initial mean curvature of the open leaf κ. According to this relationship, large, highly curved leaves release more energy and snap more rapidly than smaller, weakly curved leaves.

This situation is similar to bi-stable CFRP composite snap-through motion which is shown in Figs. 2 (a)-(d). We make an unsymmetric [0°/90°] laminated bi-stable CFRP composite and cut one of the edges in a circular manner. At first [Fig. 2(a)], the shape is stable and there is no applied force or energy. By applying the bending moment using fingers, the composite stretches widely [Fig. 2(b)], and at some instant [Fig. 2(c)], the curvature changes in a flash. Finally, as shown in Fig. 2(d), the other shape becomes stable again. This sequence is close to the description given by Mahadevan.

Given this similarity in the elastic deformation between the Flytrap's leaf and the bi-stable composite, we find the potential of a bi-stable structure for realizing the flytrap's leaf for rapid snapping motion.



(a)

(b)

Fig. 3. (a) Fiber direction diagram. (b) The top diagram represents a fiber to which the moment, M_1, is applied at both end-points of the fiber axis. The bottom diagram denotes a fiber ply to which the moment, M_2, is applied at both end-points of the fiber lateral sides.

III. CFRP BI-STABLE STRUCTURE

Unsymmetric laminates generally have two stable equilibrium configurations when cooled from their elevated cure temperature [6]. The curvatures for the two stable configurations are of opposite signs and the laminate can be changed from one configuration to the other by a simple snap-through action initiated by applying moments to the edges of the laminate. In CFRP laminated composite structures, both a thermal expansion of epoxy resin that is coated on to the CFRP and unsymmetric alignment of the carbon fiber strips render the laminated structure bi-stable.

First, the thermal expansion of the resin induces the main force that causes bi-stability. When the CFRP composite is cured at high temperature through a vacuum bagging process, the coated resin from the CFRP melts and spreads widely on the CFRP surface. Then, upon being cooled down to room temperature, the resin contracts and is hardened. Therefore, this shrinking resin pulls the carbon fiber that is attached, and generates bending moment.

At the same time, the CFRP exhibits different trends in bending for two fiber directions where one is that of the fiber's strip line axial direction and the other is the fiber's lateral side direction (see Fig. 3 (a)). In the top diagram of Fig. 3 (b), the carbon fiber itself has small elongation and high tensile strength; therefore, the cured fibers hardly bend. But in the bottom diagram, the bending moment that is applied at the lateral sides of the carbon fiber can easily bend the CFRP ply because each fiber strip is separate and the strips are connected merely by epoxy resin. If the same bending deformation is applied to each carbon fiber layer as illustrated in Fig. 3, the bending moment M_2 is smaller than M_1. Hence, this difference renders the unsymmetric laminated structure bi-stable and the composite ply needs different bending force in fiber axial direction and fiber lateral side direction.

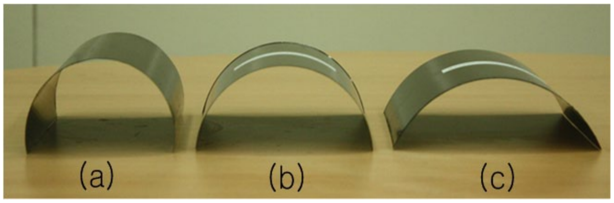


Fig. 4. Bi-stable composites with varying curvature. (a) Standard two –layered CFRP composite. (b) Insert of 100μm length kepton film. (c) Insert of 200μm length kepton film.

Due to both effects, the bending performance of an unsymmetrically laminated CFRP composite ply has directionally dependent characteristic, i.e., bi-stability. The curvature axis of the CFRP is parallel to fibers axis and it is located at curve shape inwards; therefore, the deformed curved shape of the bi-stable structure can be predicted.

The curvature of the bi-stable structure can be changed by putting a kapton film between the CFRP composite sheets. Increasing the thickness of the structure decreases the curvature. This appearance comes from stiffness of kapton film. The kapton film resists bending by resin shrinkage. In Fig. 4, bi-stable composites with varying curvature are shown. The curvature of bi-stable structure can be controlled by changing the thickness of CFRP layer as well. For CFRP layers with same resin content, ones with thick carbon filament resist bending and have small curvature.

TABLE I
CARBON FIBER MATERIAL PROPERTIES

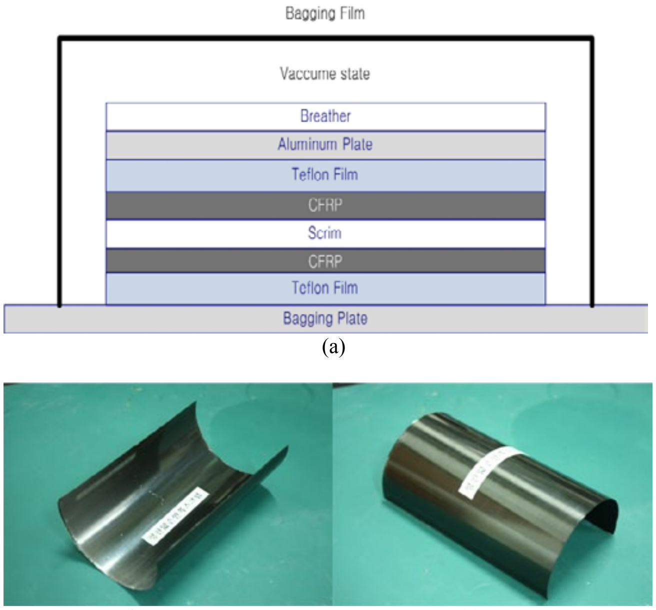
Quantity	Unit	Model CU0503	 CU1003
Tensile Strength	kgf/mm^2	500	
Tensile Modulus	kgf/mm^2	24000	
Elongation	%	2.1	
Mass per Unit Length tex	g/1000m	800	
Density	g/cm^3	1.8	
Carbon Fiber Weight	g/mm^2	54	100
Resin Weight	g/mm^2	38	61
Resin vs. Carbon fiber ratio	%	41±2	38±2
Scrim Weight	g/mm^2	34	34
Total Weight	g/mm^2	126	195
Thickness	mm	0.092	0.136

IV. MANUFACTURING

A. CFRP Composite

The CFRP of HANKUK CARBON CO. LTD. is used as a material for bi-stable structures. This material's technical information is in Table 1. Original choice is the CU0503 model because the bi-stability increases with the ratio of resin weight over carbon fiber weight (R/C) and this model has the highest value of R/C. As expected, this model also yielded the largest bi-stable curvature shape. But it was slightly weak; the edges cracked owing to the low intensity of carbon fiber and extreme thin thinness. Instead of CU0503, we used a more robust model, viz., CU1003. With the change in material, the structure's bi-stability and curvature decreased but the composite's edges became stiffer.

The manufacturing of the composite begins by cutting the



(a)

(b) (c)

Fig. 5. (a) Layout diagram for the materials for the bagging process. (b) and (c): the manufactured unsymmetrically laminated bi-stable CFRP composite structure, CU0503.

CFRP as a perfect square with a length of 150mm. A bi-stable CFRP with this length yields a curvature that is akin to a semi-sphere in CU0503 and an arc in CU1003.

To achieve bi-stability, two square plies made of CFRP were perfectly aligned [0°/90°]. Aligned CFRP was cured by high-temperature bagging for laminating CFRP composite. The conditions of the curing process were a temperature of 170C°, curing time of two hours and bagging pressure of 1atm. The set of bagging materials is illustrated in Fig. 5. The teflon film is WL 5200B, the bagging film is WL 7400 and the breather is ECONOWEAVE 1010 from AIRTECH CO. The aluminum plate caused additional mass effect and clarified the surface of the bi-stable composite. Because the bi-stable composite is manufactured as a perfect square, the curvatures in the two different stable states are of the same size but of opposite signs. After curing and cooling down to room temperature, the produced bi-stable structures have stable configuration which has a curvature. All the edges of the composite are cut for eliminating residual resin pieces that stream out cured from the CFRP.

B. *SMA Spring Actuator*

To manufacture the SMA spring actuator, an SMA wire, core rod and a drill are prepared to wind the wire around a core rod. This core rod's diameter determines the spring's diameter. SMA wire made by DYNALLOY, Inc. is used, its diameter is 0.381mm and the austenite temperature is 70C°. According to SMA coil spring actuator manufacturing method in Koh's investigations, the SMA wire is wound on a 1.6mm core-rod which is vised on the drill and a helical spring with an index of about 4.2 is produced [21]-[22]. Then, both end-points of the spring are clamped using bolts and nuts and the spring is put into a stove for annealing treatment. For this treatment, the annealing temperature is 300C° and the heating time is an hour. As the SMA wire is made into a spring shape, a large displacement is realized. Therefore, it is appropriate to induce the bending of a large curvature bi-stable composite structure. In Fig. 6, the SMA coil spring actuator is embedded in bi-stable structures and its activating process is shown. When electric current is applied to the stretched SMA coil actuator, the actuator is heated and shrinks to the original memorized length. This shrinking of the SMA actuator generates pulling force at the clamping bolt which generates bending moment on the bi-stable structure. Then the bi-stable structure's initial stable configuration is changed to the other stable configuration.

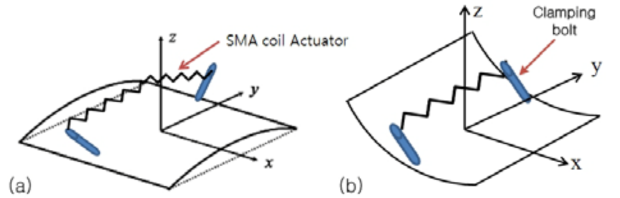


Fig. 6. Schematic of a SMA coil spring actuator activating the snap-through motion of the bi-stable structure (a) before activation (b) after activation

C. *Prototype*

The flytrap robot prototype consists of two bi-stable unsymmetrically laminated CFRP composite leaves with two parallel SMA spring actuators embedded in each leaf and a clamping holder that acts like a stem of a flytrap. The holder consists of two parts, a 3mm acrylic plate and a rapid-prototyped (RP) Y-shaped holder**.** The RP machine is Dimension 3D printer soluble support technology (SST) and resolution is about 0.254mm. The acrylic plate is cut by a laser machine; its role is to clamp the bi-stable composite leaf for keeping the leaf as flat as possible. The Y-shaped holder is for holding the two leaves and inclining their position so that they shut more tightly.

The assembly of the flytrap robot is described in Fig. 7. At first, we embed the SMA coil spring actuator in the prepared bi-stable unsymmetrically laminated CFRP composite leaf by using clamping bolts. The both end points of clamped actuators are positioned near the edge of the composite leaf with putting across. Next we set the Y-shaped holder and sandwich two acrylic plates on both sides of branches of the Y-shaped holder. The leaf is sandwiched between the acrylic plates and its shape stays almost flat.

For embedding SMA spring actuators in CFRP composites, two problems need to be addressed. One is a current leaking problem and the other is a melting problem. The first problem occurs when the SMA actuator directly touches the CFRP composite fiber, and the input current to activate the SMA actuator leaks through carbon fibers from one end of the actuator to the other. This usually occurs when the SMA actuator is embedded closer to the surface of the CFRP composites. This problem arises when the CFRP composite is drilled and bolted using a common metal bolt that holds the SMA actuator and the actuator is connected to the carbon

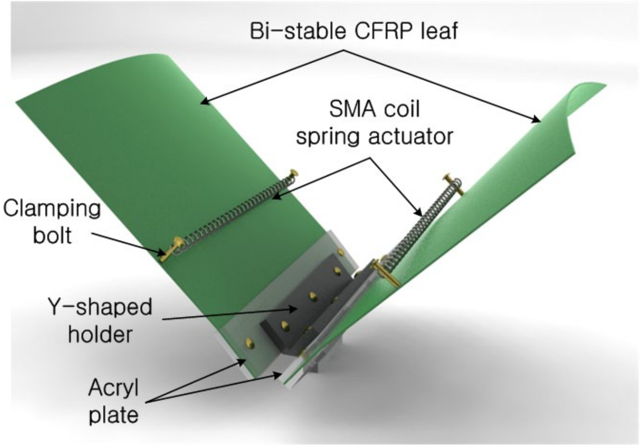


Fig. 7. Assembly of the flytrap robot.

fiber directly. To solve this problem, we use plastic bolts and nuts to electrically insulate from the carbon fiber.

However, the alternative way to solve current leaking problem using plastic bolts and nuts cause the melting problem. When current is applied to the SMA spring actuator, the actuator becomes hot due to the thermoelectric process. The heat causes the plastic bolts and nuts to melt; and the actuator to unfasten. To solve this problem, we use aluminum foil plies and install them between the plastic nuts and SMA actuators. Aluminum foil acts as a heat sink; therefore, the clamped point no longer melts through heat generation from the actuator.

Spines were made of CFRP composite fractions and attached to the sides of the CFRP composite leaves. The flytrap robot is colored in green using a lacquer spray. The total weight of the flytrap robot is 121.8g and the size is 240x80x160mm.

V. RESULTS

To compare the flytrap robot's closure motion with the Venus flytrap's motion, we use a high-speed camera and record the motion at 1500 frames per second. When an input current of 1.3A is sent at 6.7V to the SMA spring actuators, which are embedded, they pull both edges of the flytrap robot as the actuator shrinks due to thermoelectric heating.

Fig. 8 shows the sequence of the snapping motion of the flytrap robot. In the first few milliseconds until 40ms, the robot's leaves barely move but stretch in a level manner. At 50ms, the leaf snaps through and changes to the second stable curvature for closing. Then, the leaf closes rapidly for 50ms and oscillates a few times; finally, it rests. The sequence shows that the flytrap robot has a closing time of about 100ms. That speed of snapping is almost the same as the Venus flytrap's motion.

In the experiments, the snapping movement of the two leaves is not synchronous. The pitch of the SMA spring actuators does not have exactly the same. The pitch varies slightly because of errors in winding the spring and errors in the location of bolts in the composite shells. Also, the degradation of the SMA actuator causes some mismatch in the closing time.

The degradation can be explained in two ways [23]. One is excessive input current. Current is sent to the SMA spring actuator when it is in a stretched position. If the input current is so high that the SMA actuator anneals again locally, the actuator does not memorize the original shape. Instead of the first memorized shape, the actuator rememorizes the new equilibrium position, which corresponds to release in the stretched state. This phenomenon causes asynchrony in the closure.

The second cause of degradation is the excessive external force that acts in the process of release SMA spring actuator for embedding to the bi-stable composite shell. The undue external force causes the SMA spring actuator to suffer plastic deformation in some local parts. This also causes the rememorizing effect as in the first reason, and this degradation makes the actuator's performance poor.

The spines slightly degrade the curvature of the flytrap robot's leaves. The spines are attached to the leaves. The points of attachment partially flatten the edges of the leaves.

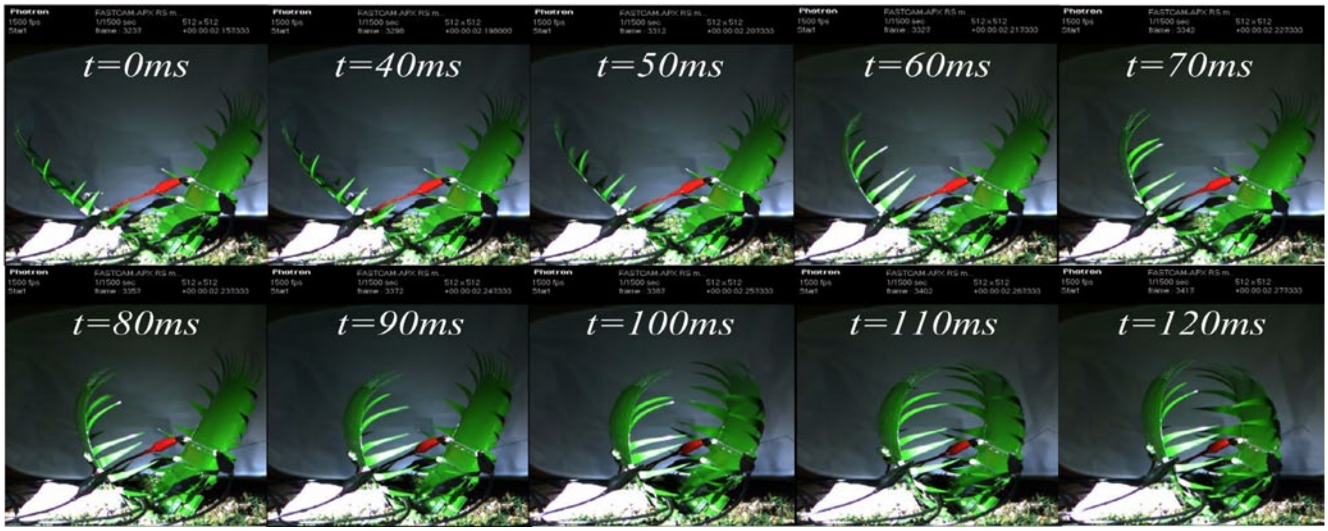


Fig. 8. Snapping sequence of the flytrap robot.

Integration of these spines weakens the total curvature of the closed shape, and the flytrap's final closure posture is not enough to trap perfectly.

VI. CONCLUSION

In this paper, we have presented a bio-mimetic flytrap robot using a bi-stable unsymmetrically laminated CFRP composite structure with SMA spring actuators. The snap-through performance of bi-stable structure is shown that it is similar with the closure motion of the Venus flytrap. The large displacement of the SMA spring actuator enables deformation of large curvature bi-stable structure. The snapping motion of the flytrap robot takes about 100ms, which is similar to that of the Venus flytrap's speed of motion. However in scalable consideration, the flytrap robot's closure speed is faster than the Venus flytrap's it because the flytrap robot has much bigger leaf than the Venus flytrap has. The bi-stable mechanism enables rapid motion with a single actuation of energy and the changed shape is maintained with an initial energy input not a continuous input energy. The applications of this flytrap mechanism and structures are based on this advantage. From this technology, fast and large shape changes can be possible and they can be applied to soft morphing product like morphing wing or rocket. Also this research will be extended to a rapid gripping mechanism with various sizes.

Future work includes structural analysis and prototype customization. The geometry and locations of the embedded actuators should be adjusted to improve performance. Also self opening ability will be developed.

APPENDIX

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