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Development of an Origami-Inspired Mechanism utilizing Soft Material

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**“Development of an Origami-Inspired Mechanism utilizing Soft Material”**

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**Project Summary:**

In this project, we proposed to extend the boundaries of origami-inspired design by exploring a new design concept, ‘soft origami.’ Typical forms of origami consist of rigid facets and flexible crease lines, and uncertainties due to distorting and stretching of material are generally considered to be an obstacle to address in this type of design. However, this project focused on the benefits of using soft materials in origami design. We designed hybrid origami structures composed of materials with various rigidities to achieve new types of building blocks for origami-inspired mechanism design. The structure with the soft material inherits the elasticity and the viscosity such that the functional parts such as springs and dampers can be implemented without compromising the simplicity of the structure. These components will extend the design boundary of origami mechanisms beyond the usual transformable structures into unique new mechanisms. We demonstrated the proposed design concept through two research accomplishments.

The first topic is ‘dual-mode morphing origami.’ With the softness of the material, additional morphing modes with different levels of deformation energy can be embodied in the origami structure, which can be used for a variety of motion creation. We addressed this possibility by implementing an origami-inspired kinematic design made entirely of stretchable materials. Traditionally, folding is the only way that the origami structure could change, so the energy level for morphing is only defined for folding movements. However, stretchability of facets can provide new morphing mode within different energy spectrum. By compositing these dual-morphing patterns based on various traditional origami frames, we show the generality of the design principle and demonstrate the potential of soft robots capable of extreme motion generation.

The second topic is ‘morphing origami block.’ The research proposed a design approach that complements the drawbacks of an actuator by utilizing structural characteristics of origami. The elasticity of material can provide a design space for structural characteristics using a unique response derived from material compositions with different stiffnesses. We characterized structural characteristics as energy pathways and energy gradients in the morphing behavior that determines the dynamic properties, which have generally been ignored in origami designs. In morphing origami block, we implemented bi-stability through the energy barrier design and solved the stability problem, which is a drawback of shape memory alloy actuator. We believe the proposed actuation design approach will increase the achievable range of activeness for origami's abundant design resources and will open up rich application field in origami-inspired engineering.

Additionally, we would like to present works on the extension of the previous research (2013~2016). In previous research, we had been exploring the potential of origami-inspired design with and emphasis on the benefits of compactness, lightweight and easy fabrication of transforming mechanisms. By improving the design methodology established in the previous research, this vision was developed into ‘transforming tire’ that can be applied to a real scale vehicle, and ‘flat foldable robotic arm’ that can be folded into sheet shape but has high rigidity and lightweight. These accomplishments can be representative examples of proving the potential of origami.

## Research Performance:

### ○ Dual-Morphing Soft Origami

The research introduces an entirely soft origami-inspired deployable structures that are driven by the pneumatic input. Because the structures we developed are only composed of soft stretchable elastomers, we were able to achieve two-step motion by the single pneumatic input. The primary motion is similar to the behavior of origami structure so we call ‘deploying motion’ because the structure deploys as the pressure is applied. In this phase, the displacement is mainly associated with rigid translations and rotations of material elements of the folding line, resulting in the area of facets almost unchanged. As the pressure is further applied after the structure is fully deployed, the secondary motion occurs which is similar to the behavior of fluidic soft actuators so we call ‘functional motion’ because the deployed structure performs a function such as bending, twisting, or bloating depending on their design. In this phase, the displacement is mainly associated with straining, resulting in the area of facets largely changed. This two-step motion offers advantages of high compactness and dual-modality. In addition, by designing the two-step motion differently, complex motion can be realized with a single input.

The fundamental form of an entirely soft origami frame is a set of soft facets linked in a zigzag form by soft crease lines. The difference in energy levels required for geometric unfolding and material strain can decouple the morphing modes of the soft origami frame under the applied strain: (i) geometry-dominant origami-like deployment ( $0 < \lambda < 15$ ) and (ii) material strain-dominant body stretching ( $15 < \lambda < 25$ ) (Fig. 1A). Because the deployable kinematic patterns based on parent origami frames have kinematic degrees of freedom to generate unfolding within low energy levels, the first origami-like morphing mode can occur with relatively small stress on the material (Fig. 1B). The same principle was designed into the dual-morphing mechanism of Sorogamis. We developed one typical design for Sorogamis based on the parent Miura-ori polyhedron (thus, termed as “M-Sorogami”) with structural modifications for fluidic actuation (Fig. 1C).

M-Sorogami consists of a set of c-channel fluidic network (facet-crease-facet) with an origami-inspired design that avoids the structural interference between adjacent facets when rotating. Applying air pressure to the M-Sorogami preferentially induces the geometric transformation of the soft crease lines from a diamond shape to a square shape. Additional pressurization shifts the dominance of the M-Sorogami morphing from the origami-like rigid translation to the strain-dominant asymmetric motion.

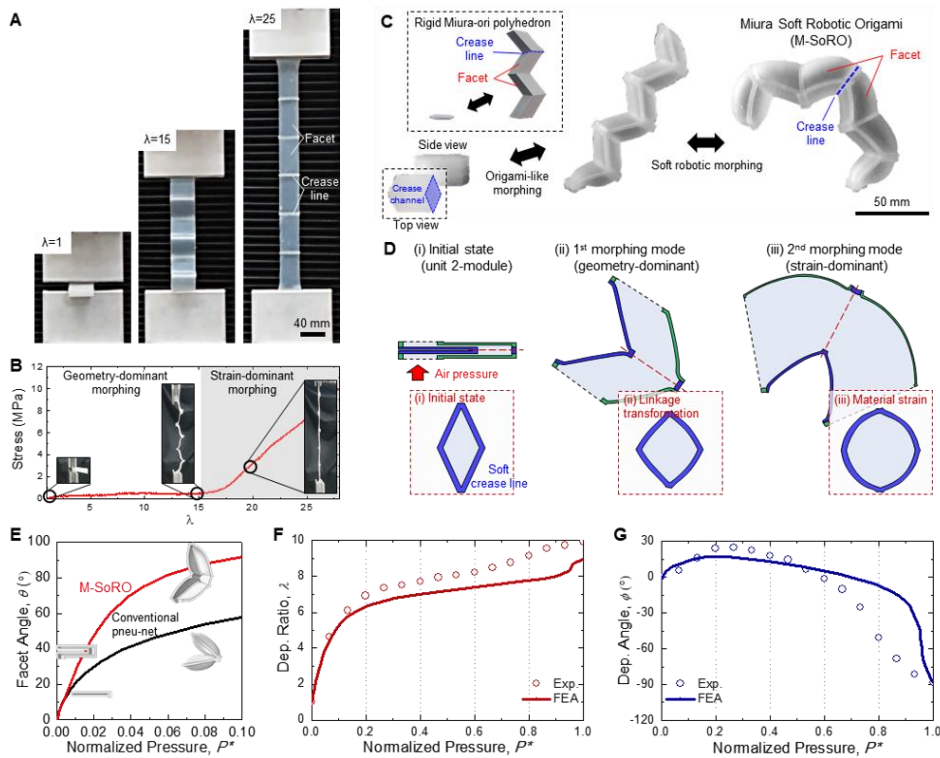
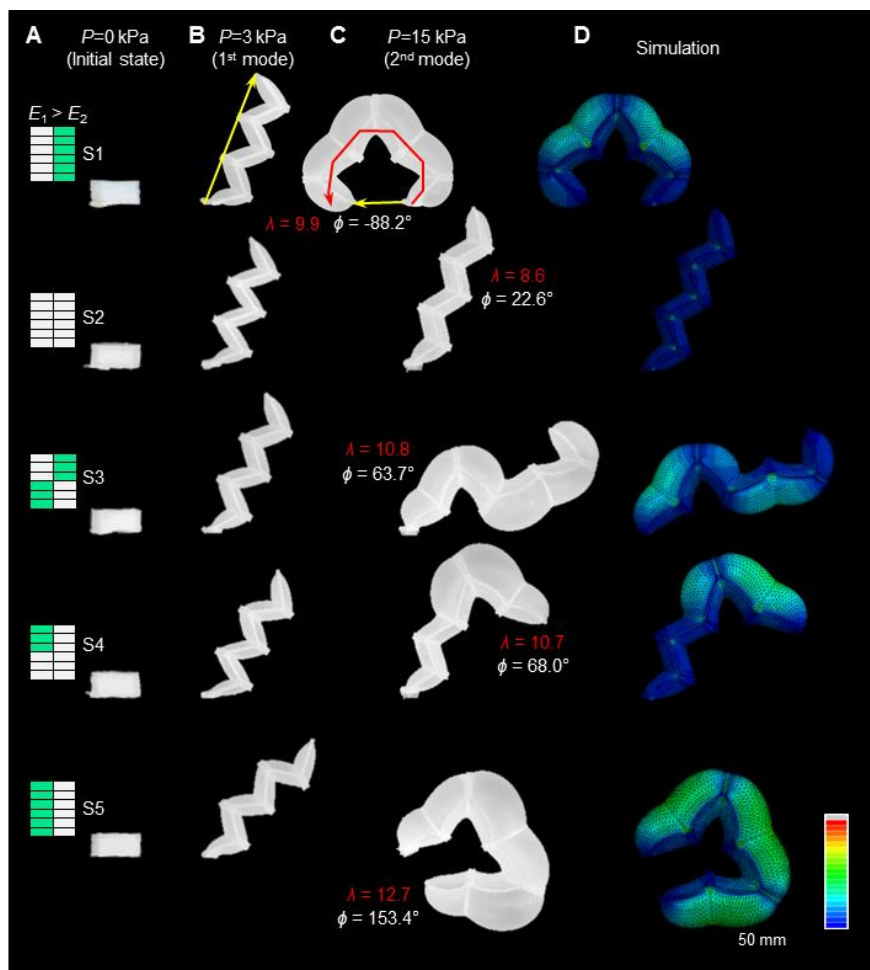


Figure 1. Principle of dual-morphing origami

In this second morphing mode, extreme stretching of the soft facets and crease lines induces an asymmetric balloon-like expansion of the Sorogami frame, called a ‘hidden’ soft robotic morphing, due to the engineered distribution of material stiffness (Fig. 1C). It also indicates that the geometry of the soft crease lines crucially affects the origami-like deployment morphing and enables the Sorogami to be more than twice as effective as the conventional pneumatic network design for extreme shape development by unfolding (Fig. 1D). By contrast, the increase in  $w$  delays  $P_{trans}$  (Fig. 1E), while saturating the similar  $\theta$  value with the increasing applied pressure.

The morphing behavior of the N-module M-Sorogamis can be characterized by the coupled response of  $4N$  possible combinations. Five representative 6-module M-Sorogamis with distinct material disposition were demonstrated for experimental instantiation of the programmed pseudo-sequential dual-morphing and the possible range of robot configurations (Fig. 2). The geometry of the M-Sorogamis was designed identically for all cases, but different combinations of material disposition were patterned to each side of the stacked modules using two different elastomers. The experimental results show that the geometry-dominant unfolding (1st morphing mode at  $0 < P \leq 3$  kPa) of the M-Sorogamis generated similar deployment vectors (yellow arrows,  $\lambda \approx 7$ ) regardless of the material disposition (Fig. 2B). During the strain-dominant soft robotic morphing (2nd morphing mode at  $3 < P \leq 15$  kPa), however, the deployed M-Sorogamis started to deform into a programmed direction, producing a ‘hidden’ motion (Fig. 2C). All M-Sorogamis could deploy about 10 times (or more than) their initial length, and their morphing could be predicted accurately by the finite-element simulation results (Fig. 2D).

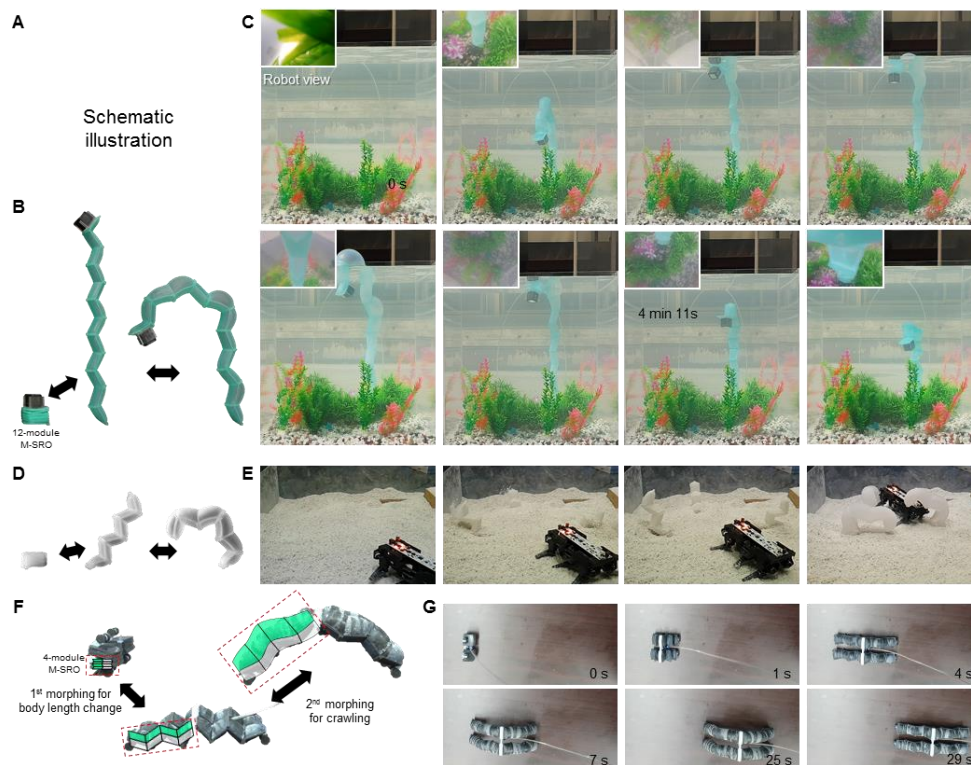
The dual-morphing capabilities of M-Sorogamis feature extreme changes in body shape with a wide range of morphing configuration and have potential for delivering unrevealed functionalities, such as initial compactness, structural deployment and hidden robotic motion, to conventional soft robotic applications. Inspired by the eye tentacle of terrestrial snails, we demonstrated a soft robotic eye



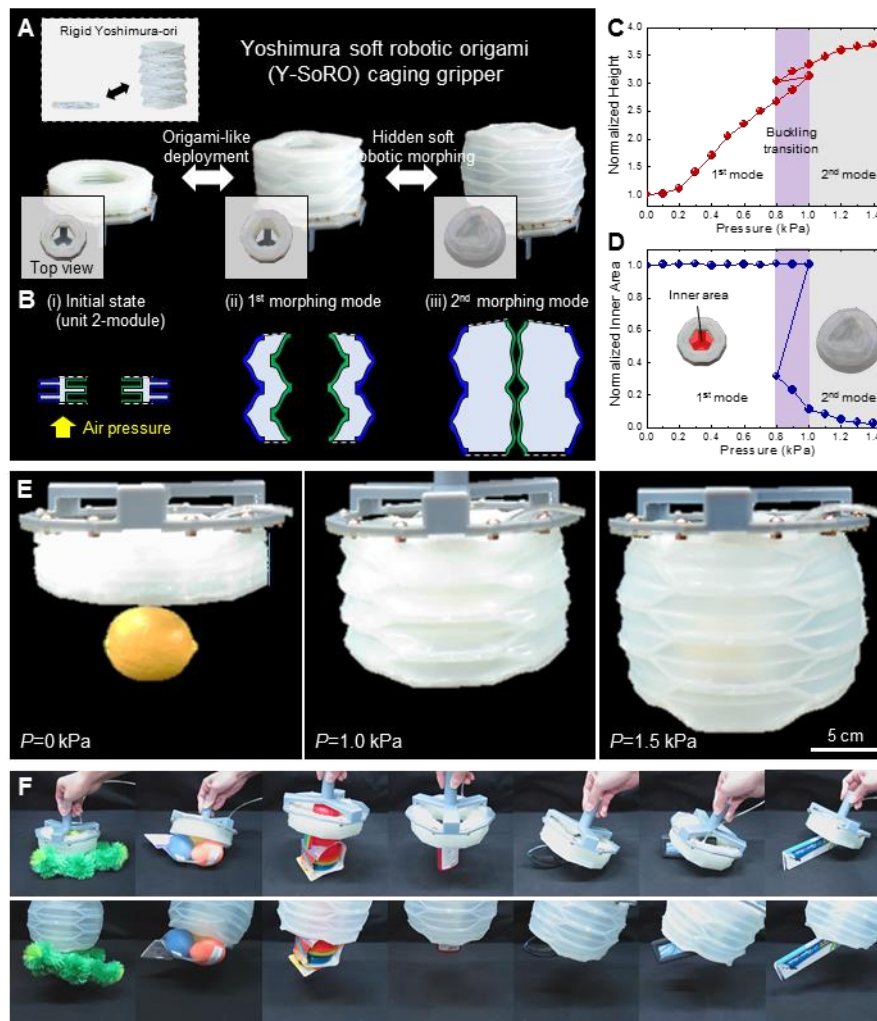
**Figure 2.** Behavior of dual-morphing origami

tentacle that use a dual-morphing mechanism for a wide field of vision (Fig. 3). When pressurized, the robot grew, with the help of buoyancy, up to 60 mm through an origami-like morphing until its end tip touched the surface of the water. Subsequently, the robot could cover a wide field of vision via the secondary morphing (Fig. 3C). Because the origami-inspired design is initially compact (thin and folded), it is easy to integrate multiple elements in confined spaces and to create combinatorial responses of extreme shape development. In this respect, we demonstrated the cooperative actuation of M-Sorogamis to provide unique robotic gripping and locomotion abilities. We constructed a soft robotic gripping system using three 6-module M-Sorogamis in which the second morphing mode was regulated for bending (Fig. 3D). The ability to change their length extremely from an initially compact design allowed the system to be portable and concealed inside an unstructured environment such as a heap of sand. Each M-Sorogami gripper could protrude out of the sand through an origami-like morphing (Fig. 3E) and could subsequently actuate towards  $\phi = -90^\circ$  for its task ( $< 1.3$  s). In another demonstration, we integrated four 4-module M-Sorogamis to create a deployable soft crawler (Fig. 3F).

A type of parent origami frames and the geometry of their soft facets and crease lines can diversify the dual-morphing response of the Sorogamis. We constructed a different class of fluid-driven Sorogamis based on the parent Yoshimura-ori cylinder (thus, termed as “Y-Sorogami”). In contrast with the M-Sorogami, the Y-Sorogami has strengths in producing asymmetric bloating with the limited body length change. To show the benefits of the dual-morphing behavior of the Y-Sorogami, we demonstrated a deployable soft caging gripper that exploits morphological computation for universal grasping in a previously inaccessible manner (Fig. 4A). The gripper was made from two Y-Sorogami cylinders with different radius and material stiffness. The stiffness of the inner cylinder was designed to be lower than that of the outer one, in order to induce asymmetric inward bloating (Fig. 4B, i). The Y-Sorogami gripper is initially a folded design (height=35 mm) and, when pressurized, preferentially deploys in the height direction by unfolding (Fig. 4B, ii), and then the inner facets enclose the object through the secondary asymmetric bloating (Fig. 4B, iii). We found that the transition between the two morphing modes occurs at  $P \approx 1$  kPa with some buckling instabilities (Fig. 4C and D). Importantly, two pseudo-sequential modes are functionally separated in terms of grasping ability: the first origami-like morphing triggers only a body length change and the second soft robotic morphing performs the task of grasping by reducing the inner area of the gripper (Fig. 4D).



**Figure 3.** Performance demonstration. (B,C) Underwater camera device that can have a wider view with dual morphing. (D,E) Gripper to hold an object from compact state. (F,G) 3D printed soft crawler



**Figure 4.** Deployable gripper Y-sorogami

### ○ Morphing Origami Block

The research introduces the structural design methodology to overcome the deficiencies of the actuators and expand the achievable range of deformation for shape-programmable architecture. Because a behavior of a system is the result of the interaction between the actuator and the structure, these unique characteristics of the structure can be combined with the actuator to achieve advantageous features that cannot be achieved by the actuator alone, which we call synergetic effect between actuation elements. The proposed actuation concept is demonstrated by presenting a morphing origami block as a discretized actuation unit of shape-programmable architecture. From the synergy of three key actuation elements (i) actuator element - torsional shape memory alloy wire (TSW) actuator pair, (ii) morphological element - modularized block pattern, and (iii) physical element - bi-stable structural characteristic, the system is capable of fast and reversible morphing but can also be stabilized after morphing. The proposed actuator design concept is not limited to TWSMA actuators but also can be used to supplement deficiencies in various types of artificial muscle actuators.

As an actuator, the torsion shape memory alloy wire (TSW) actuator is chosen from a variety of options for origami folding because of a large torque, a high response speed, reversibility, and large actuation angle despite having a small form factor. TSW actuator is built into origami structure and can actively fold the origami using twisting motion of the shape memory alloy (SMA) wire (Fig. 5 D). A simple wire is aligned with the fold line, and each end is fixed to a facet. When the wire is heated, it twists and generates a torque that rotates the joint. Since the SMA is easily actuated by electricity through the wire, selective and addressable actuation of distributed SMA actuators can be achieved.

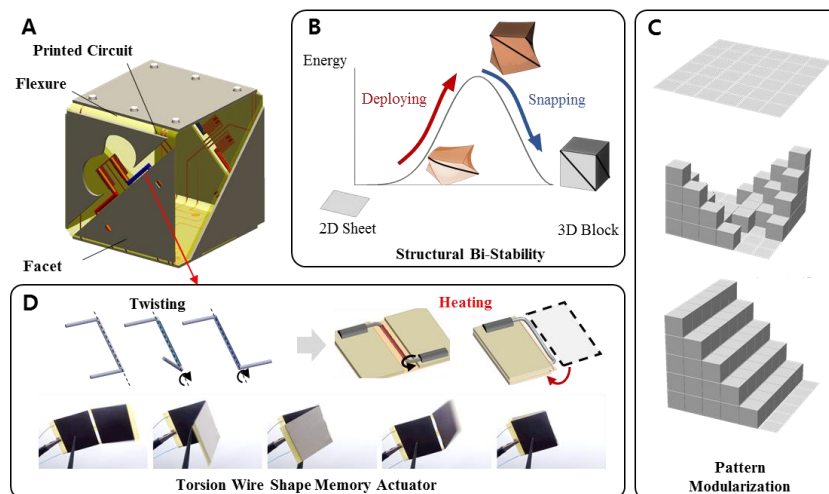
Including these features, a large number of actuators must be precisely controlled to achieve high DOF actuation for shape programmability. As with most artificial muscle actuators, however, it is difficult to precisely control the movement of the TSW actuator. Morphological property can complement the limited accuracy of the actuator by creating a highly definitive output shape through modularization. We discretize the entire morphing into a number of identical morphing blocks with simple on-off transformations (Fig. 5 C). The block can change its own volume and expand into 3D space in a packed layout, and the on-off shape switching of each block allows the entire architecture to be transformed into a target 3D shape without the need of precise folding angle control and complex folding algorithm.

This discrete, step-wise shape generation approach improves accuracy at the expense of shape diversity similar to analog-to-digital signal conversion. Therefore, the resolution to reproduce various shapes, the number of the individual blocks, becomes an essential issue. The limits of the resolution in physical implementation is mainly determined by the load capacity and stability to physical disturbance which determine the stackable numbers of the blocks. However, most of artificial muscle actuators including SMA actuator are difficult to have both high force and stabilization feature (stiffening without motion). High energy density of TSW actuator provides high driving force but TSW actuator is unable to be stiffened without accompanying motion and additional energy consumption. Physical property of the structure can solve this issue by providing the structural stability. The bi-stable physical property using kinematical over-constraint allows fast snapping transformation triggered by TSW actuator and mechanical stability at target shapes without the force from the actuator (Fig. 5 B).

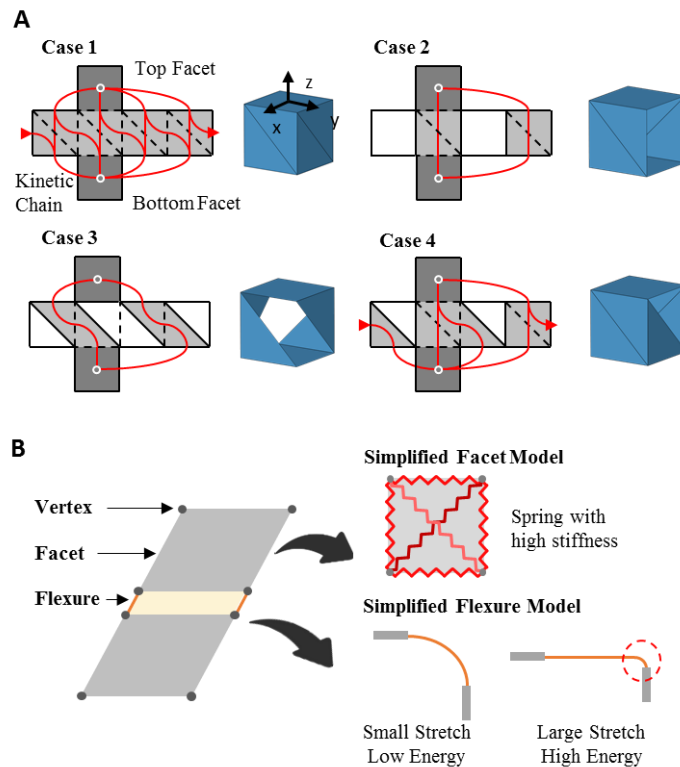
The origami pattern of the block consists of two types of parts made of different materials: a rigid facet, a linkage of the structure and a flexible flexure, a joint which connect the facets. The response of each part with different stiffness leads to a unique physical property which can be design space for physical property tuning. Here, we use the geometrical factors to tune the physical property: a disconnection of the pattern usually called kirigami and a variation of the flexures width. A disconnection of the pattern changes the skeletal structure of the block which causes the different mode of deformation, so it is used to design the stability for mechanical disturbance. The flexure width determines the degree of resistance when the body deforms through a particular mode, so it is utilized in the design of the energy barrier for the state transition.

Fig. 6 A presents the possible cases of the facet disconnection. Because the block is overly constrained, the top and bottom plate are connected through multiple kinetic chains marked with the red lines. The kinetic chain in a closed loop reduces the movement freedom so that it helps to achieve the desired movement. Since the block has multiple closed loops, there is room to greatly change the physical property of the structure. However, the effect of the kinetic chain is hard to be predicted with general kinematic and kinetic because of complex three-dimensional deformation. To quantitatively examine the effect of the facet disconnection, a simplified truss model was built (Fig. 6 B). The facet is assumed as a combination of trusses (virtual linear springs) and the deformation of the facet is substituted by compression of the springs while stretching is not allowed.

Along with the facet deformation, the flexure also provides the extra mobility in over-constraint condition. Here, we simplified the flexure behavior model by focusing on the effect of the



**Figure 5.** Design details of the morphing origami block

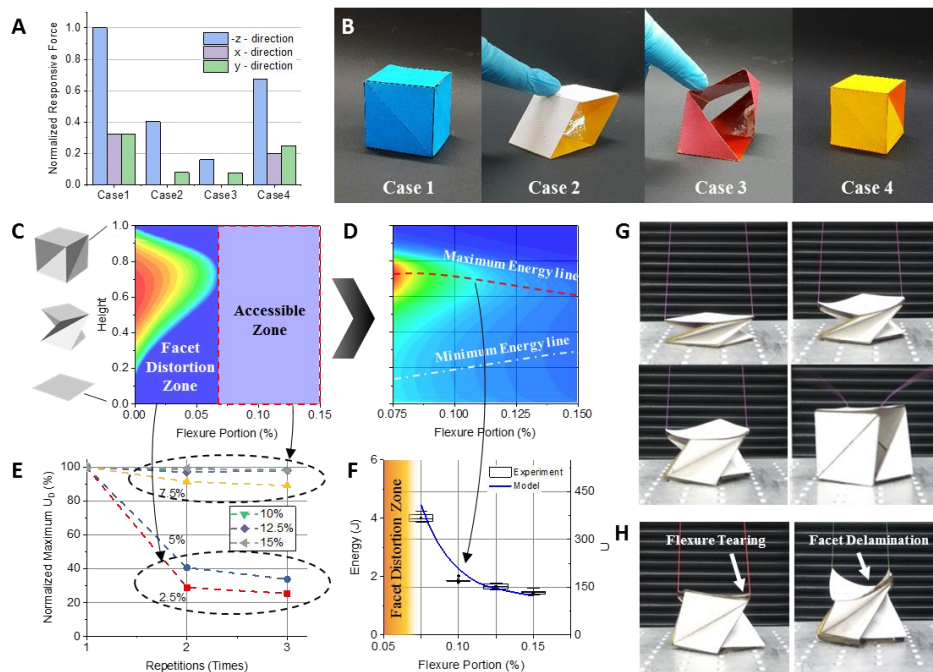


**Figure 6.** Schematic diagram for physical property estimation

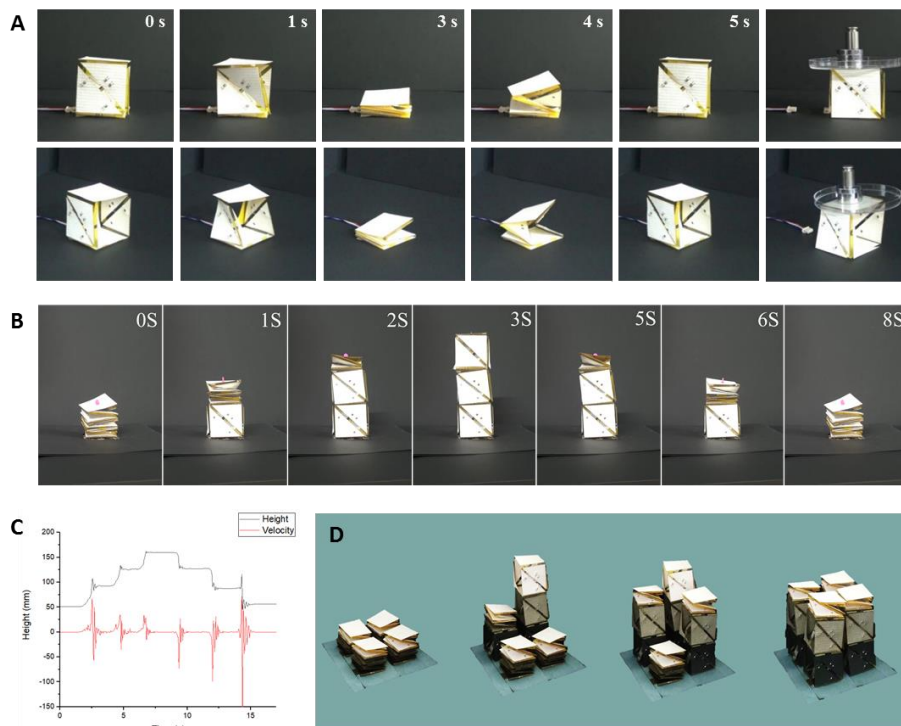
flexure deformation on the internal energy. When pure bending is applied to the flexure, the curvature is evenly distributed throughout the flexure to minimize the energy. Facet dislocation, however, forces the translational deformation of the flexure which increase the energy. We assumed the crucial factor in the energy change is the concentration of the curvature; when the flexure is pulled by the facet dislocation and the curvature is concentrated, the energy is greatly increased (Fig. 6 B).

Fig. 7 A shows the response to the disturbance calculated from the model, and Fig. 7 B shows the actual image of the blocks. For each case, the resistive forces were investigated by applying 0.2 unit of displacement to the top facet in x, y, -z direction. Case 1 is the original pattern without disconnection. Full of the kinetic chains provides high disturbance resistance in all direction, but the four layers of facets between the top and the bottom facet thicken the structure when fully folded. Case 2 has a simple circular loop of the kinetic chain with four side facets. Removing the side facets solves the interference and thickness problem, but causes undesired excessive movement freedom resulting in low resistive force in x directional disturbance. Case 3 is another variation of the side facets. The twisted kinetic chain causes kinematical over-constraint, but it lacks mechanical stability as it can make large displacements with small facet deformation. Case 4, the selected pattern, has half number of the kinetic chain with three side facet on each side. The superposition of the kinetic chain in different shape arouse high resistance in all direction.

Fig. 7 C presents the amount of the facet deformation as the flexure width changes. Since the facets have higher stiffness than the flexure, it requires high force to deform, as well as cause structural failure and delamination due to accumulation of damage. Thus, in the design of the physical properties, we concluded that it is desirable to avoid the facet deformation and to use the flexure deformation to pass through a kinematically undefined region. The model predicts that about 7.5% flexure width is a marginal point that does not require the facet deformation. For the region with the flexure width greater than 7.5%, the flexure deformation model is used to predict the behavior of the structure and the result is presented in Fig. 7 D. To verify the estimation, we performed two types of experiments with six different specimen: performance degradation due to repeated actuation and maximum deformation energy change. Fig. 7 E plots the degradation of the maximum deformation energy. As predicted through the model, the performance was drastically decreased at 2.5% and 5%, and maintained at more than 7.5%. Small flexures cause large deformations in the facet (Fig. 7 G) and consequently structural failure (Fig. 7 H). Fig. 7 F shows maximum deformation energy acquired from the experiments and the theoretical expectations. The result shows that these two data show a similar trend.



**Figure 7.** Theoretical and experimental analysis of the physical property



**Figure 8.** Implementation of the origami blocks and the shape-programmable architecture. (A) Single morphing origami block can transform itself between 2D sheet and 3D block shape, within a couple of seconds per each transformation, and it have a structural stability at each target state. The block can support more than 50 times of its own weight without the actuator force. (B) Transformation of multi-layered blocks and (C) its height change versus time (D) Performance of shape-changing ability of  $2 \times 2 \times 3$  multi-block system which reconfigures its shape into diverse three-dimensional configurations from flat substrate.

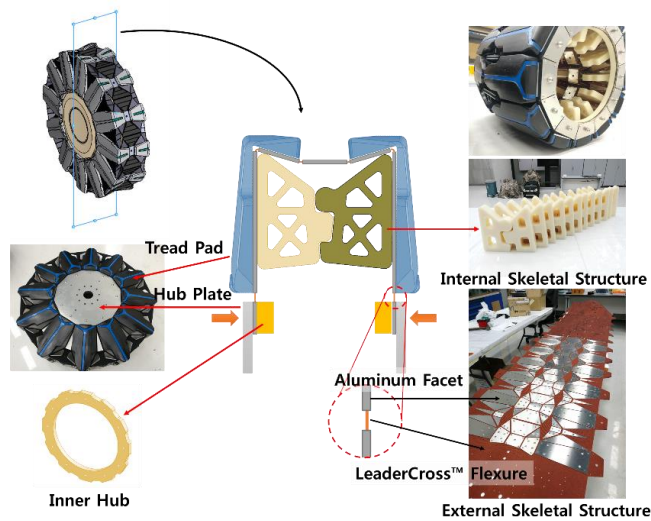
The demonstration presents the single block of 50mm length with a weight of 6g. The morphing takes less than one second and the fully deployed block can support more than 50 times of its own weight in the vertical direction. As illustrated in Fig. 8 A, a single block can transform its shape between 2-D flat sheet and 3-D cubic block as current is applied. By the multi-layer arrangement of the single origami block, the system can be expanded in 3D space. We built a shape-programmable architecture in a  $2 \times 2$  matrix form with identical three-story column (Fig. 8 D).

○ **[Spin-off Project] Transformable Wheel**

A wheel is one of mankind's oldest and best inventions and has been used for most mobile devices and vehicles. In previous research, we propose a variable-diameter wheel design which combines the function of deformable wheel and airless tire by using a soft material based origami-inspired design. By simply folding a patterned sheet into a wheel shape, a variable-diameter wheel was built without lots of mechanical parts and a complex assembly. The proposed wheel structure is capable of greatly enhancing the mobility of its applied devices that require to move in various environments such as an exploration robot in an extreme area and personal mobility. As a next stage, we and Hankook Tire Co. have collaborated to create a futuristic transformable tire concept, enhanced version of the origami wheel. This extreme application of compliant mechanism can stand more than 1,600 kg.f and the diameter can change from 400 mm to 800 mm (Fig. 9 and 10).



**Figure 9.** A prototype of transforming tire project



**Figure 10.** Composition of transforming tire

○ [Spin-off Project] Foldable Robotic Arm

\* Science Robotics, Mar. 2018 Cover (Fig. 12)

\* Top 10 Best mechanical engineering technology of 2018, Korean Federation of Mechanical Engineering Societies (Fig. 12)

A foldable arm is one of the practical applications of folding. It can help mobile robots and unmanned aerial vehicles (UAVs) overcome access issues by allowing them to reach to confined spaces. The origami-inspired design enables a foldable structure to be lightweight, compact, and scalable while maintaining its kinematic behavior. However, lack of structural stiffness has been a major limitation in the practical use of origami-inspired designs. Resolving this obstacle without losing the inherent advantages of origami is a challenge. We solve this issue by implementing a simple stiffening mechanism which utilizes an origami principle of perpendicular folding. The simplicity of the stiffening mechanism enables an actuation system to drive shape and stiffness changes with only a single electric motor. The results show that this design is effective for a foldable arm and allows a UAV to perform a variety of tasks in a confined space (Fig. 11).

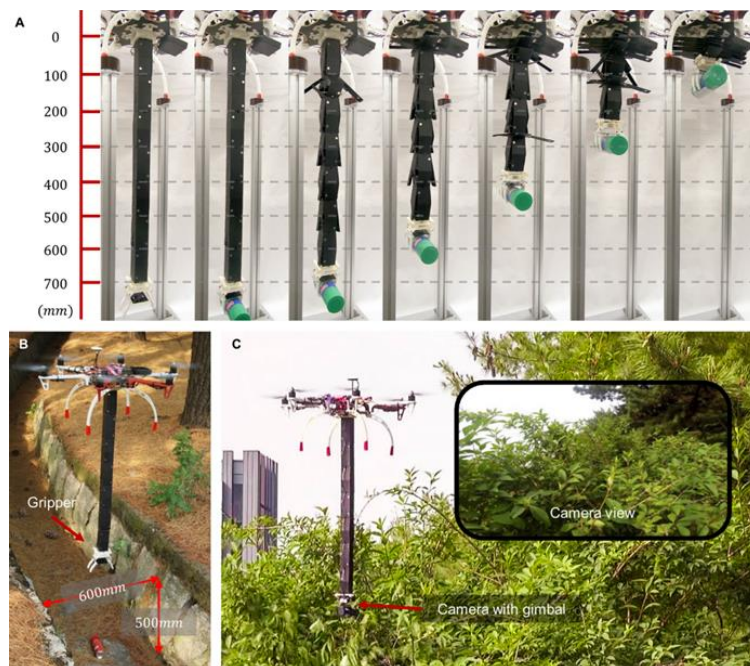


Figure 11. Foldable robotic arm applied to retrieval operations using a UAV



Figure 12. Science Robotics Cover (Left), Top 10 Best mechanical engineering technology of 2018, Korea (Right)

## **Results and Discussion:**

In the previous stage of the project (2013~2016), we proposed origami-inspired mechanisms that replaces the conventional rigid components while achieving the benefits of origami - lightweight, and simplicity. The origami transformable wheel, the result of the previous project, developed into the transformable tire project and proved that the proposed origami mechanism can be applied to a real-scale vehicle so that it demonstrated the potential of the origami-inspired mechanism design. The flat folding manipulator also demonstrated how to take advantage of thin, light and strong origami-inspired mechanism.

In this stage of the project (2016~2018), we conducted a study on soft origami that utilizes softness of materials to provide additional functionality to the origami-inspired structures. By changing the flexibility of origami, overall energy profiles could be adjusted. The modified energy profile offers additional functionalities like snap-through motion and two-mode expansion. Using soft origami, it is possible to make the origami block module and the soft deployable structure with special functionalities embodied in the structure. From the results, we have confirmed that the soft origami structure can function more than just as a frame.

In the future, we will investigate the possibilities of integrating multiple functionalities into a single component. A robotic system normally requires various functional components such as a frame, joint, damper, and spring. If various functions can be embedded into a single component, it will enable multi-functional systems with simple actuation. Mechanical simplicity can increase the robustness of the system, lower production costs, allow the system to be scalable.

**List of Publications and Significant Collaborations that resulted from your AOARD supported project:** In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

**a) papers published in peer-reviewed journals,**

- S.-J. Kim, D.-Y. Lee, G.-P. Jung and K.-J. Cho, "An origami-inspired, self-locking robotic arm that can be folded flat," *Science Robotics*, Vol. 3 No. 16, 2018.
- D.-Y. Lee, S.-R. Kim, J.-S. Kim, J.-J. Park, and K.-J. Cho, "Origami Wheel Transformer: A Variable-Diameter Wheel Drive Robot Using an Origami Structure," *Soft Robotics*, vol. 4, no. 2, May. 2017

**b) papers published in peer-reviewed conference proceedings,**

- W.-b. Kim, J.-k. Kim, and K.-J. Cho, "Deployable soft bending actuator", in *IEEE ICRA 2017*.
- S.-R. Kim, D.-Y. Lee, J.-S. Koh, and K.-J. Cho, "Fast, Compact, and Lightweight Shape-Shifting System Composed of Distributed Self-Folding Origami Modules," in *IEEE ICRA, 2016*, pp. 4969-4974.

**c) papers published in non-peer-reviewed journals and conference proceedings,**

- N/A

**d) conference presentations without papers,**

- Woong-Bae Kim, Kyu-Jin Cho, "Soft Robotic Origami Structures: Highly Deformable and Configurable Soft Robots," *IROS 2018 workshop on shape changing robotics structures and interfaces, 2018*.
- Dae-Young Lee, Kyu-Jin Cho, "Stiffening of Transformable Structure via Structural Locking," *IROS 2018 workshop on shape changing robotics structures and interfaces, 2018*.

**e) manuscripts submitted but not yet published, and**

- N/A

**f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.**

- Hankook Tire Co. 4<sup>th</sup> The Next Driving Lab Advertising Film Project – Transforming Tire

**Attachments:** Publications a), b) and c) listed above if possible.

**DD882:** As a separate document, please complete and sign the inventions disclosure form.

**Important Note:** If the work has been adequately described in refereed publications, submit an abstract as described above and refer the reader to your above List of Publications for details. If a full report needs to be written, then submission of a final report that is very similar to a full length journal article will be sufficient in most cases. This document may be as long or as short as needed to give a fair account of the work performed during the period of performance. There will be variations depending on the scope of the work. As such, there is no length or formatting constraints for the final report. Keep in mind the amount of funding you received relative to the amount of effort you put into the report. For example, do not submit a \$300k report for \$50k worth of funding; likewise, do not submit a \$50k report for \$300k worth of funding. Include as many charts and figures as required to explain the work.