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Deployable Soft Composite Structures

Wei Wang[1], Hugo Rodrigue[1,2] & Sung-Hoon Ahn[1,2]

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Deployable structure composed of smart materials based actuators can reconcile its inherently conflicting requirements of low mass, good shape adaptability, and high load-bearing capability. This work describes the fabrication of deployable structures using smart soft composite actuators combining a soft matrix with variable stiffness properties and hinge-like movement through a rigid skeleton. The hinge actuator has the advantage of being simple to fabricate, inexpensive, lightweight and simple to actuate. This basic actuator can then be used to form modules capable of different types of deformations, which can then be assembled into deployable structures. The design of deployable structures is based on three principles: design of basic hinge actuators, assembly of modules and assembly of modules into large-scale deployable structures. Various deployable structures such as a segmented triangular mast, a planar structure comprised of single-loop hexagonal modules and a ring structure comprised of single-loop quadrilateral modules were designed and fabricated to verify this approach. Finally, a prototype for a deployable mirror was developed by attaching a foldable reflective membrane to the designed ring structure and its functionality was tested by using it to reflect sunlight onto to a small-scale solar panel.

There is currently significant interest in low-cost, lightweight, and compactly packable deployable structures for various types of missions, especially when the structure needs to be compact during a certain phase of the mission and easily deployable during another, such as space missions. Deployable structures have been used to deploy antennas, solar panels and masts of satellites, and they require good stability in the deployed configuration to support structural loads and to resist external disturbances. Most conventional deployable structures are highly complex structures making use of numerous mechanical components such as linkages, hinges, motors and energy storage devices[1]. However, this generally leads to large-sized mechanisms and complex assembly processes that make them heavy, complex and high-cost[2].

Certain articulated deployable structures such as the able deployable articulated mast (ADAM) and the large deployable antennas (LDAs) use complex linkage mechanisms resulting in a large structural mass in order to obtain a good performance during deployment[3,4]. However, recent advances in functional materials and structures that are easy to control, inexpensive, and capable of continuous deformations have opened new doors for engineers to design deployable structures with compact systems. These advances have not only been driven by the aerospace industry, but also by industries in diverse fields such as rescue robots, architecture, and many more because this kind of structure enables the integration of multiple functions into a single design to make it interact more effectively with its environments[5–7]. Shape memory polymers (SMPs) are polymeric smart materials that have the ability of recovering from a deformed shape to their original shape induced through the application of an external stimulus. SMP-based bending actuators capable of continuous deformations have been developed as well as bending hinges for foldable and deployable structures[8–11]. SMP composites (SMPCs) with higher strength and elastic modulus have been studied to fabricate a deployable truss which can unfold and has a low stiffness after being deployed[1]. Shape memory alloys (SMAs) can recover a limited amount of strain and can subsequently restore their original shape when heated[12,13]. SMAs have a shorter response time and higher actuation stress in comparison with SMPs. However, SMAs have a small working strain which limits their use in applications where large deformations are required. Smart soft composites (SSCs) combining SMA elements and a soft matrix use the limited strain of SMA wire to generate complex, large and continuous deformation of the matrix[14–18].

Deployable structures are generally composed of linkages where the elements are connected to each other using mechanical joints and, through the strategic positioning of these elements and connections, can accomplish a stable deploying process and maintain its configuration either in the folded or unfolded state. To succeed in a

[1]Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, 151-742, Korea. [2]Institute of Advanced Machines and Design, Seoul National University, Seoul, 151-742, Korea. Correspondence and requests for materials should be addressed to S.-H.A. (email: ahnsh@snu.ac.kr)

truly integrated environment, deployable structures need to reconcile the inherently conflicting requirements of low mass, good shape adaptability, and high load-bearing capability although the available design solutions invariably carry intrinsic limitations[19]. Morphing structures with variable stiffness are an effective method to realize shape adaptation since they can realize large deformations at low stiffness and can maintain their shape at high stiffness[20]. Therefore, structures with variable stiffness capabilities represent a promising solution for tackling the conflicting requirements of deployable structures. Various studies demonstrate variable stiffness structures using embedded phase changeable materials in a flexible matrix which can undergo a significant stiffness reduction by applying to the embedded material a temperature higher than its phase transition temperature, and that this type of concept can be easily integrated with other types of structures[21,22]. However, this solution requires a relatively long transition time for both stiffness reduction and stiffness recovery because of the required heating and cooling times, which confines this type of structure to applications without strict time requirements. Fluidic flexible matrix composites or inflatable structures that work by opening and closing their inlet valves and jamming consisting of numerous small granules that can change from a flexible to a solid state after vacuuming can also achieve a wide range of stiffness[23,24]. Nevertheless, these structure are inseparably connected with mass appendants, which increase their integration requirements.

Our previous work on smart soft composite (SSC) actuators has demonstrated an actuator capable of variable stiffness and of large actuation capable of retaining a deformed shape by combining phase changeable materials with an SSC actuator[25]. Although there are limitations in terms of cooling times, a number of applications requiring deployable structures do not have strict time limits such that this type of structure presents significant potential for these applications. This research introduces an actuator combining hinge-like deformations and shape retention capabilities for implementation in deployable modules and structures. This was accomplished by embedding variable stiffness material along with stiff elements into a soft matrix. The described hinge actuators are capable of variable stiffness and continuous morphing and can be used to construct deployable structures based on three principles: design of basic hinge actuators, assembly of modules and assembly of modules into large-scale deployable structures. To verify the proposed principles, deployable structures of a triangular mast, a planar structure and a ring structure were designed and fabricated based on different module designs. Finally, a prototype for a deployable mirror was developed and its functionality was tested by using it to reflect sunlight onto to a small-scale solar panel.

Results and Discussion

Actuator fabrication process.

The basic design used in this work is that of a self-actuating SSC hinge actuator possessing both soft morphing and shape retention capabilities with a locally bendable section embedded with phase changeable materials. This SSC structure combines smart materials, a flexible matrix and an embedded rigid structure. Smart materials can be placed eccentrically from the neutral surface of the matrix structure with either smart material being placed towards one side or two sides to make the hinge actuator capable of either unidirectional or bidirectional bending deformations. In this research, SMA wires with a diameter of 0.152 mm are used as the smart material, polydimethylsiloxane (PDMS) elastomer as the flexible matrix, fusible alloy (FA) of Field's metal as the phase changeable material and acrylonitrile butadiene styrene (ABS) for fabricating the embedded rigid structure throughout all actuators, and all materials used are commercially available (see Supplementary Information). PDMS is a translucent and flexible elastomer with low thermal conductivity and high thermal stability that can withstand the strain of the embedded SMA, but a number of other polymers, fabrics, composites and other flexible and elastomeric materials could also be used for the matrix. The phase changeable material used is Field's metal with a melting point of 62 °C which is within the useful temperature range of the PDMS matrix, although many other fusible alloys and thermoplastics are also available. This fusible alloy is non-toxic, has a high thermal conductivity, low viscosity in the melted state and high-stiffness in the solid state. Ni-chrome (Ni-Cr) wires with a diameter of 0.15 mm are embedded in the FA structures and applying an electrical current to these wires will result in melting of the FA structure. To prevent the electric current going through the fusible alloy rather than the Ni-Cr wire, the Ni-Cr wire is covered with an electrically non-conductive polyimide (PI) tube with inner and outer diameters of 0.18 mm and 0.20 mm, respectively. The main properties of the SMA, PDMS and PI tube are shown in Supplementary Tables S1, S2 and S3, respectively.

The minimum atmospheric temperature for proper functioning of the actuator is determined by the lower bound of the useful temperature range of the polymeric matrix, which is −45 to 200 °C for the PDMS matrix used in this work. However, the maximum atmospheric temperature for proper functioning of the actuator is the temperature below which none of the embedded materials begin their respective transformation. These are the melting point temperature of the FA, 62 °C for Field's metal, and the Austenite start temperature at which the SMA wires begin recovery, 62 °C for the SMA material used. Thus, using the proposed materials, the range of atmospheric temperature in which the actuator can be used is −45 to 60 °C.

The first step in the fabrication process of the actuator is to use 3D printing to fabricate the mold structure as well as the embedded rigid structure. A fused deposition modeling (FDM) machine is used to print both structures. The rigid structure itself also contains a sub-mold which, when assembled with a cover, allows for casting of the FA structure directly at its intended position on the rigid structure. This sub-mold has holes on both sides to allow for positioning of the Ni-Cr wire covered with the PI tube into the FA structure (Fig. 1A). The FA is pre-melted in a beaker at temperature of 80 °C in an environmental chamber, and then the liquid FA is drew by a plastic syringe and injected into the mold. After 30 s at room temperature, the ABS surrounding the FA structure is cut and removed using a knife (Fig. 1B). Afterwards, the rigid structure containing the FA structure along with the SMA wires are placed in a second mold with small holes for positioning of the SMA wire. Both ends of the SMA wires are clamped using copper connectors to prevent sliding between the SMA wires and the PDMS matrix. The PDMS solution with a weight ratio of 10:1 monomer to hardener is mixed, degassed and poured into the actuator mold containing all components (Fig. 1C). The assembly is then thermally cured at a temperature

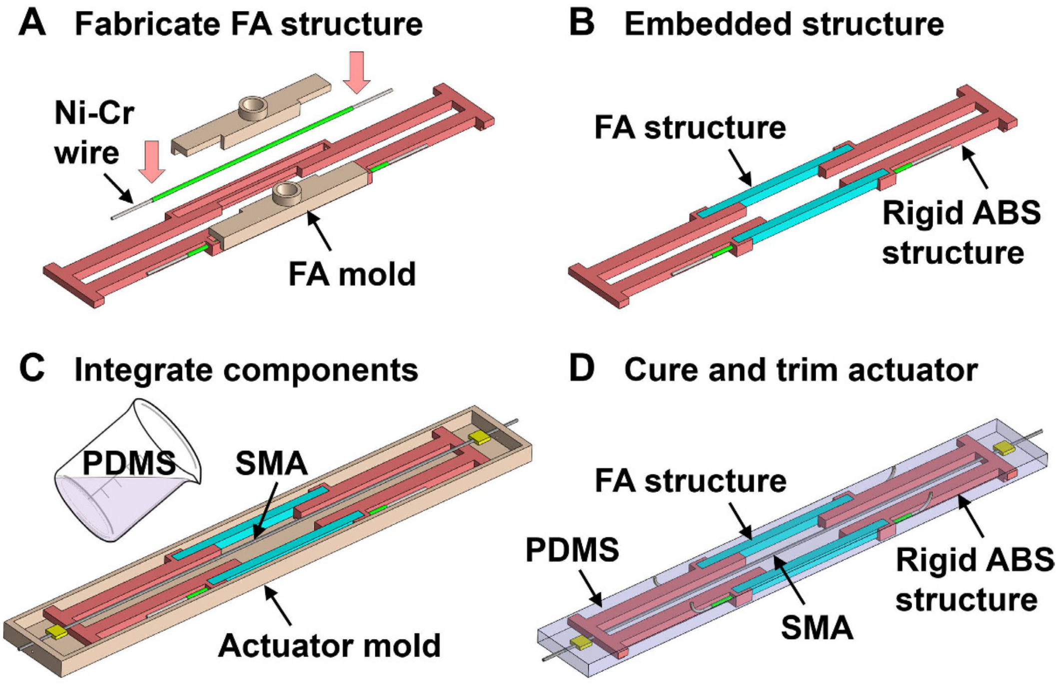

Figure 1. Schematic diagram outlining fabrication process of the basic actuator. (**A**) The FA structure is casted using mold with features to embed the PI tube covered Ni-Cr wire. (**B**) The FA mold is removed to obtain the embedded structure of actuator. (**C**) The embedded structure and the SMA wire are placed in the mold of the actuator, and then the pre-mixed uncured elastomer is poured into the mold. (**D**) The assembly is thermally cured and the mold of the actuator is removed to obtain the finished actuator.

of 55 °C for 10 h. The mold of the actuator is then removed to obtain the actuator (Fig. 1D) and electric wires are connected to each end of the SMA wires.

Actuator performance. An hinge actuator with overall dimensions of 100 × 15 × 3 mm (length × width × thickness) is fabricated where the length of the hinge segment is 20 mm. The dimensions of each FA structure are 40 × 2 × 2 mm (length × width × thickness) such that it has a 10 mm overlap with the rigid structure on each side to ensure a smooth bending deformation and a good stability under high stiffness, and the configuration of the fabricated actuator is illustrated (Fig. 2A). The actuator is capable of varying its stiffness by changing the phase of the embedded FA structures. An electric current of 1.0 A was applied to the Ni-Cr wire for 40 s to change the phase of FA structure from the solid state to the liquid state, resulting in the actuator switching from the high stiffness state to the low stiffness state. In the low stiffness, the configuration of the actuator can be changed easily through an external load (Fig. 2B). The actuator turns back to the high stiffness state after cooling of the FA structure through heat dissipation, and in the high stiffness state the actuator is capable of sustaining external loads (Fig. 2C). The bending modulus of the actuator was also tested under the two different stiffness states and result shows that the high stiffness state has a bending modulus of 137.08 MPa and the low stiffness state of 3.47 MPa, which corresponds to a ratio of approximately 39.5 times (Fig. 2D; Supplementary Equation S1). If the actuator is folded in the direction where the SMA wire is near the external surface of the actuator, applying a current of 0.6 A to the SMA wire for 8 s and of 1.0 A to the Ni-Cr wire will results in recovery of the deformed shape to the original shape by making use of the elastic potential energy from the structure and the actuation force of the embedded SMA wire (Fig. 2E; Supplementary Video S1). The resistance of the SMA wire in the martensite state is 6.2 Ω and of each Ni-Cr wire of 3.8 Ω for the given actuator configuration. It can thus be estimated that the power required for actuation if 2.2 W for the SMA wire and 3.8 W for each Ni-Cr wire, and that the total energy consumption for the entire actuation process is 321.9 J.

Deployable triangular mast. The basic hinge actuator presented in the last section can be used as a type of self-deployable linkage element with a hinge point that can be assembled as a module. These modules can then be assembled to form large-scale deployable structures. To illustrate this concept, a module is first built by connecting two triangular platforms through three hinge actuators using passive mechanical revolving joints (Fig. 3A,B; Supplementary Fig. S1). The loading capability of the module is tested by using a universal test machine applying a load to the center of the upper platform when the hinge actuators are in the high stiffness state (Fig. 3C). The stiffness of the module with the hinge actuators in the low stiffness state is not tested since the module cannot keep its deployed shape when the hinge actuators are in the low stiffness state and no current input is given to the SMA wires. The capabilities of the module to self-deploy was then tested from the folded state to the deployed state. The initial condition of the module is when all hinge actuators are fully folded at 180° and in the low stiffness state. If the three hinge actuators are deployed asynchronously, the upper platform will have three

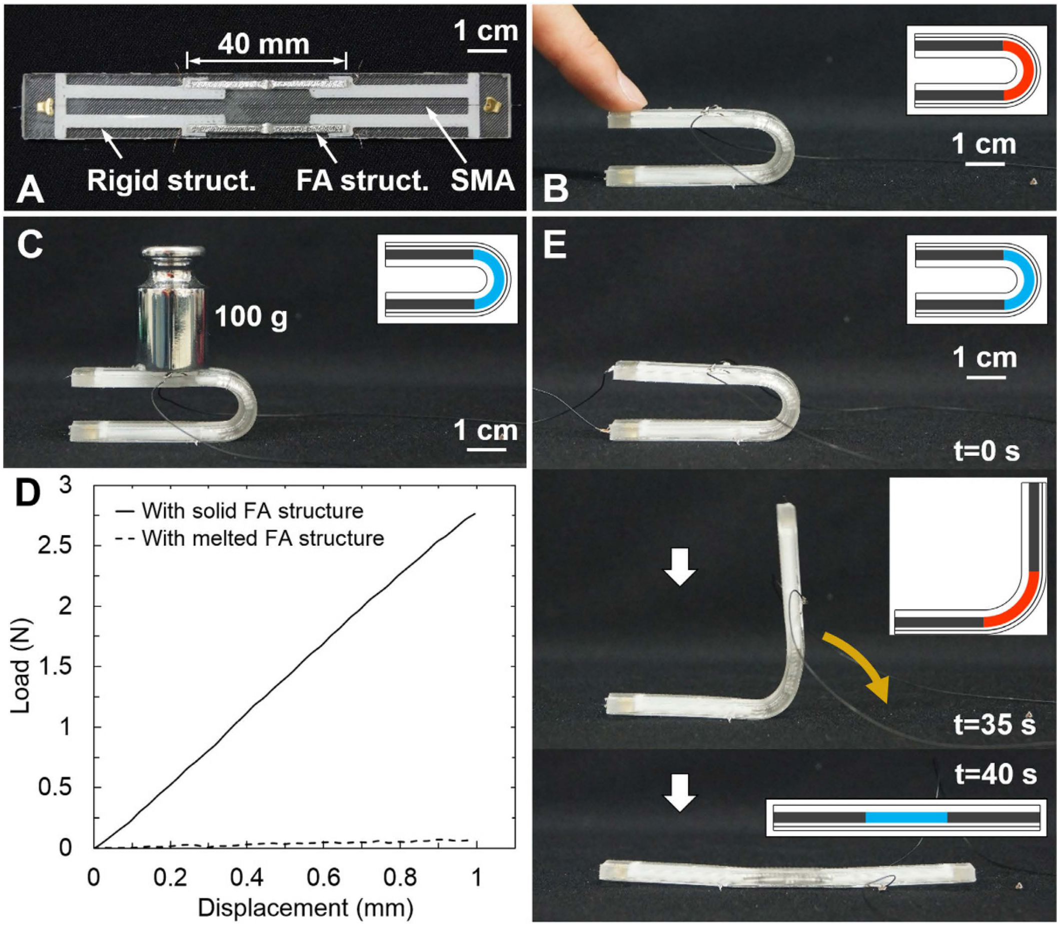

Figure 2. Fabricated hinge actuator and its performance. (**A**) Top down view of the fabricated actuator. (**B**) Actuator bent to a folded state in the low stiffness state after melting the embedded FA structures (liquid state is in red color and solid state is in blue in schematics). (**C**) Bent shape of the actuator in the high stiffness state supporting a weight of 100 g. (**D**) Results of the load-displacement test of the actuator in the low and high stiffness states. (**E**) Folded actuator deploying automatically by changing to the low stiffness state and actuating the SMA wire.

degrees-of-freedom (DOF) including two rotary DOF and one linear DOF with respect to the fixed bottom platform. Thus, the three hinge actuators should be actuated synchronously to ensure that the module deploys only in the linear direction. Therefore, the FA structures of the three hinge actuators were connected in series to melt the FA structure simultaneously, and the SMA wires of the three hinge actuators were also connected in series to obtain a smooth linear deployment (Fig. 3D; Supplementary Video S2). The height of the folded and deployed module are 30 mm and 130 mm respectively. Three such modules were then assembled in series to form a deployable mast, containing a total of nine hinge actuators, in order to test the potential for such modules to be assembled into a larger scale deployable structure. The mast was then deployed in the horizontal position from an initial state were all modules are in the folded state. It could be observed that the three modules of the mast deployed smoothly and synchronously (Fig. 3E; Supplementary Video S2). The length of the folded and deployed mast are 82 mm and 379 mm, respectively, which shows that its deployable ratio is approximately 4.6.

Single-loop modules with two-way transformation. The simple hinge actuator and structures mentioned above can only change from the folded state to the deployed state while the full inverse transformation is not possible. This is due to the required length of the actuator to obtain a full range of actuation from the deployed state to the folded state being longer than the limited length of the actuator. Based on our previous studies of hinge actuators, both the length of the flexible hinge and the length of the rigid segments should also be long to maximize the deformation, which is not possible with a limited length. To solve this problem, single loop modules composed of multiple hinged structures are presented that are capable of both deploying and folding transformations. The hinged structures are connected together at each ends using passive mechanical revolute joints to form a single loop module that can switch between the folded and unfolded states with a smaller available range of motion from the hinge structures. Two planar single-loop modules are proposed with hexagonal and quadrilateral shapes. The hexagonal module consists of a six-bar mechanism with six revolving joints and three DOFs where two actuators with two hinges each form an hexagonal structures in the deployed state and a small

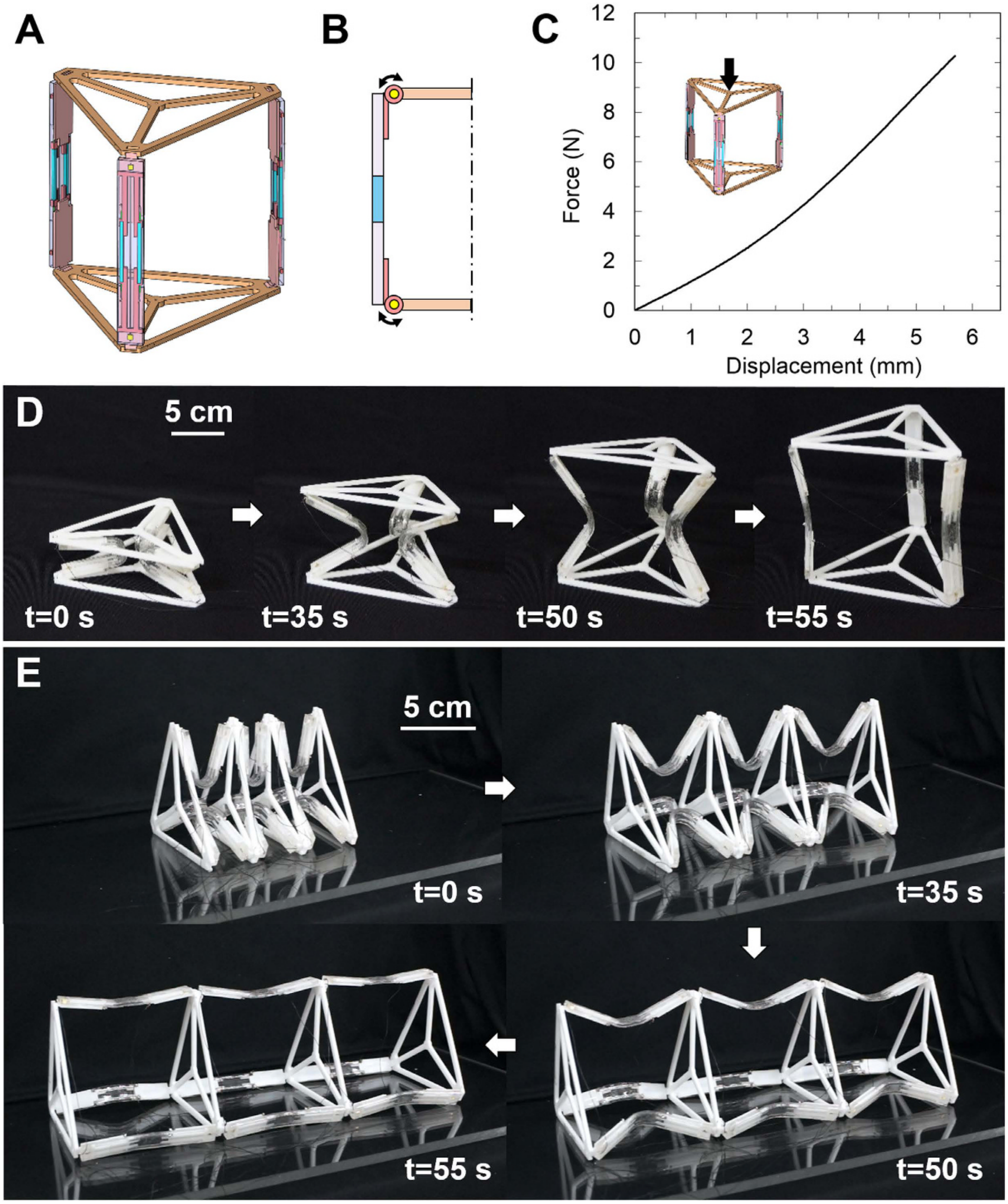

Figure 3. Triangular masts and their deploying process. (**A**) Schematic of the module assembled by three hinge actuators in parallel. (**B**) Sketch of a hinge actuator connected to both platforms through two passive mechanical revolving joints. (**C**) Load capability of the module structure is evaluated by applying a load to the center of the upper platform with the actuators in the high stiffness state. (**D**) Deploying configurations of the folded module in the same scale. (**E**) Deploying configurations of the triangular mast comprised of three modules in series in the same scale.

structure in the folded state (Fig. 4A,E). Although the structure has redundant actuation such that the number of hinge with actuation is more than the DOFs of the structure, since the structure is symmetric it can be smoothly and symmetrically deployed and folded when both actuators are simultaneously deformed (Fig. 4B). A four-bar mechanism with four revolving joints has a single DOF, so a quadrilateral module built using two compliant hinge structures similarly provides a single DOF resulting in a simpler single-loop module. However, the deformation is asymmetrical unlike the hexagonal single loop module. The developed quadrilateral module has one compliant hinge structure without SMA wires embedded in the matrix and one with two embedded SMA wires to generate the deploying and folding bending deformations (Fig. 4C,E). Then, the two hinge structures are connected using passive mechanical revolute joints to form a single-loop module. When the hinges are in the low stiffness state, actuating SMA-1 will result in the module being deployed and actuating SMA-2 will result in folding of the module, and both the deployed and folded configurations can be kept without energy consumption when the hinges are in the high stiffness state (Fig. 4D).

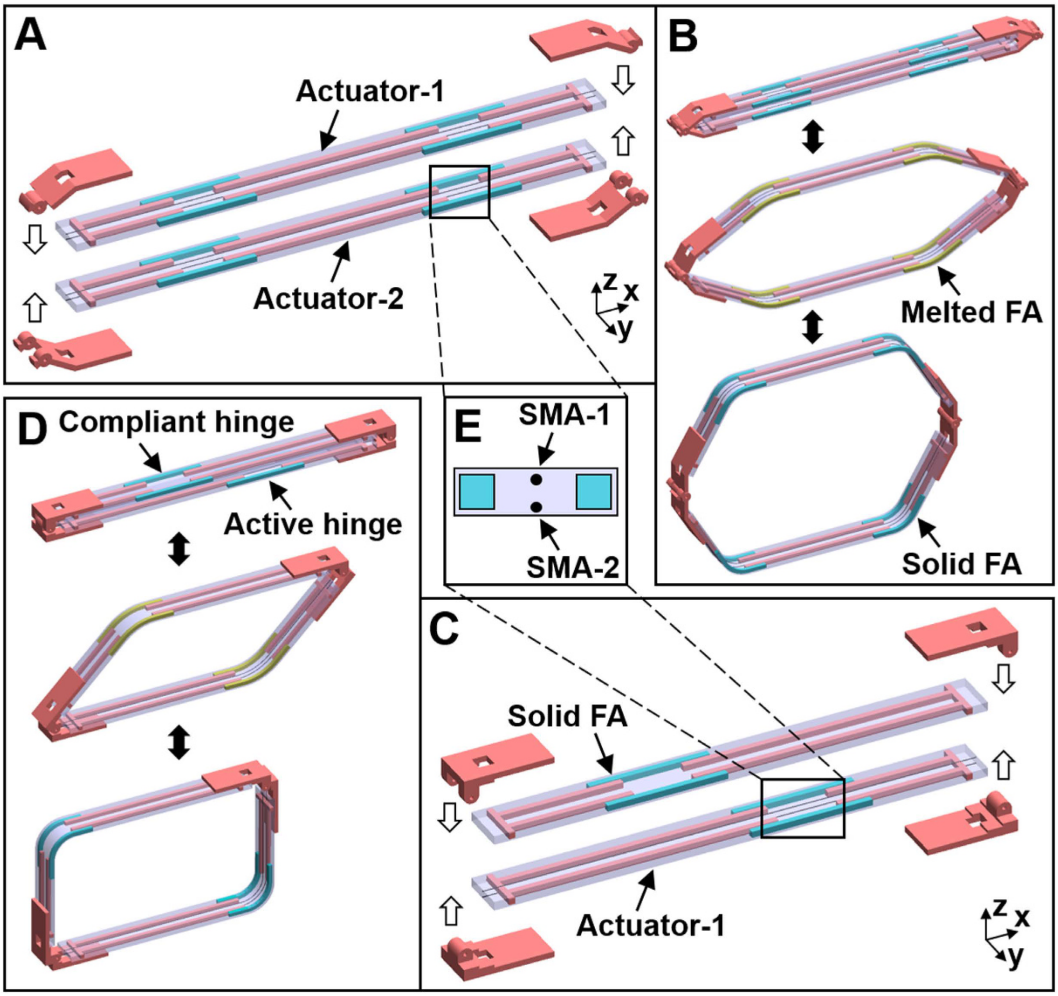

Figure 4. Schematic of hexagonal and quadrilateral single-loop modules. (**A**) Schematics of the components to form a hexagonal module and (**B**) the folding and unfolding process with the blue and yellow colored FA structures representing its solid and melted states, respectively. (**C**) Schematics of the components to form a quadrilateral module and (**D**) the deploying and folding process. (**E**) Cross-section of the actuator showing the position of the SMA-1 and SMA-2 wires embedded in the matrix.

Planar deployable structure. A hexagonal module based on the previously introduced design is created and tested to show its deploying and folding motion. The actuators used the module have a length of 190 mm and two uniformly distributed bendable sections spaced 80 mm apart with the length of each bendable section being 15 mm. When the hinge is in the low stiffness state, actuating SMA-1 or SMA-2 will result in a deploying process or a folding process, with the folded, intermediate and deployed states shown in (Fig. 5A). The capability of these hexagonal modules to be used as tiles to form an extended planar deployable structure with a large area is investigated. Tiling is usually expressed by the number of polygons around any cross point in a fixed direction order[26]. There are two possible shapes for edge-to-edge tiling of a non-regular hexagonal module (Fig. 5B). Here, the first tiling configuration is chosen to demonstrate the capability of the proposed design due to the configuration of the single loop structure. Four hexagonal structures are assembled together to show the possibility for this structure to be expended as a large network in two planar directions. In the *x*-direction, the two adjacent hexagon structures are connected using scissor-like joints with a limited revolving angle of 120° (Fig. 5C; Supplementary Fig. S2). Because of the scissor-like joints, the adjacent hexagon structures can be deployed interdependently and synchronously. In the *y*-direction, the two adjacent hexagon structures are bonded together through the rigid segment. Therefore, during the deploying process, the entire structure will expand in the *y*-direction coupled with a corresponding contraction in the *x*-direction. The height of the structure expands from 45 mm to 224 mm and the ratio in height between the deployed and folded structure is approximately 5 (Fig. 5C; Supplementary Video S3).

Ring deployable structure. Then, a quadrilateral module based on the previously introduced design is created to verify the capability of this actuator to form a 1-DOF single-loop module. The actuators used the module have a length of 160 mm and their bendable length is 20 mm. When the hinge is in the low stiffness state, actuating SMA-1 or SMA-2 will result in a deploying process or a folding process, with the folded, intermediate and deployed states shown in (Fig. 6A). Assembling multiple such 1-DOF single loop modules using passive

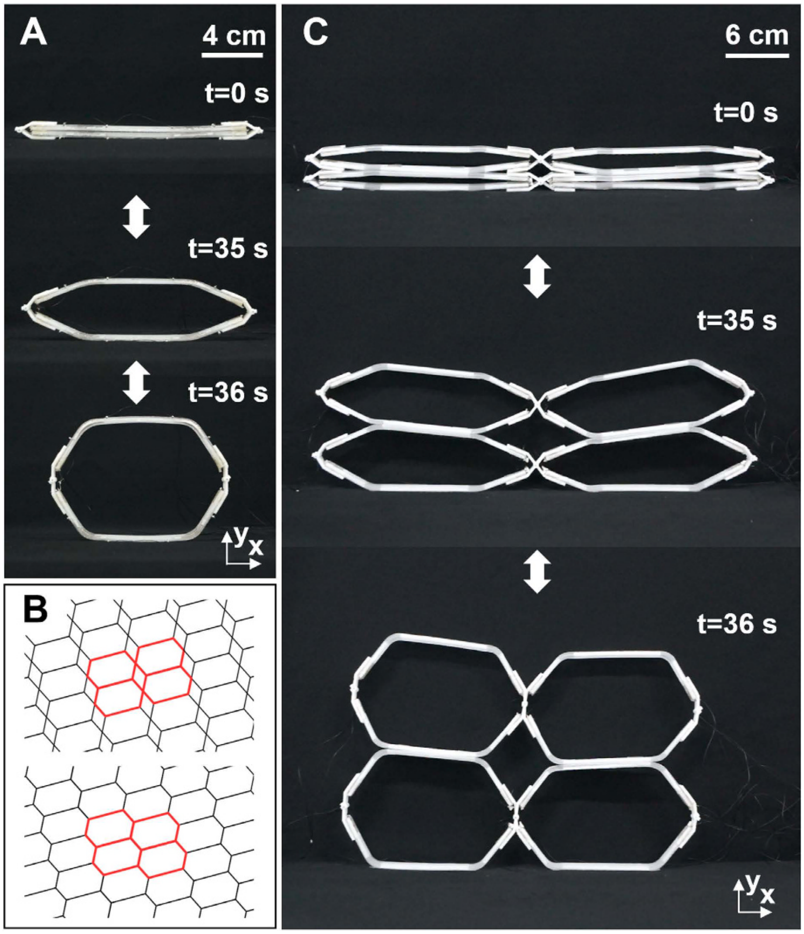

Figure 5. Deploying processes of hexagonal single-loop module and its assembly. (**A**) Deploying process of a hexagonal looping module from a compact folded state to a fully deployed state. (**B**) Schematic of the two types of tiling can be applied for assembly into an extended structure using hexagonal modules. (**C**) Front view of the deploying process of the planar structure with the first tiling pattern composed of four basic hexagonal modules.

mechanical joints, it is possible to form large-scale deployable structures. A ring deployable structure with a high extensible area ratio is proposed using multiple quadrilateral modules where each module corresponds to one edge of a flat two-dimensional structure (Fig. 6B; Supplementary Fig. S3). To illustrate this concept, six basic quadrangular modules are assembled into a six-edge ring shape configuration. This assembled structure can be folded and fixed in a compact state with the active hinges in the high stiffness state. Under a low stiffness state, the whole structure can transfer from a compact folded state to a fully deployed state by actuating the corresponding SMA wires (Fig. 6C,D; Supplementary Video S4), and can then transform back from the deployed state to the folded state by actuating the antagonistic SMA wires. The assembled structure can be folded into a cylinder volume where the diameter of the cross-section is 9.4 mm, and it can be deployed its a cylindrical volume whose cross-section has a diameter of 26 mm. Thus, the extensible area ratio is approximately equal to 8 and could be increased using a larger amount of modules to form a ring deployable structure with more edges or using actuators with a longer length.

Deployable structures for reflective mechanism. One area of interest for this kind of deployable structure is for aerospace applications. To show its functionality, a reflective mechanism is designed for rovers making use of solar-based power systems even when entering caves where direct access to sunlight is not available. When executing space missions, a rover has two options for power: radioisotope thermoelectric generator (RTG) or a solar-based power system. RTGs are expensive and quite bulky, while solar-based power systems are cheap and reliable. However, solar-based power systems should be always exposed to sunlight to generate power, and will not work without direct access to sunlight such as when the rover enters caves and other areas that are permanently shadowed. One method to solve this problem is to use strategically placed deployable mirrors to bring light into these environments[27]. Furthermore, due to the restrictions of aerospace applications these deployable structures should be compact and lightweight. A deployable mirror based on the ring-shape deployable structure is demonstrated that is low cost and has a simple deploying mechanism to accomplish repeatable deploying and folding deformations in order to be usable throughout multiple missions. Based on the previously presented six-edge ring deployable structure, a reflective membrane is cut into a hexagonal shape with an edge length 100 mm and is fixed to the deployable structure by using a cable-based tensegrity structure (Fig. 7A). In this Figure, the cables in

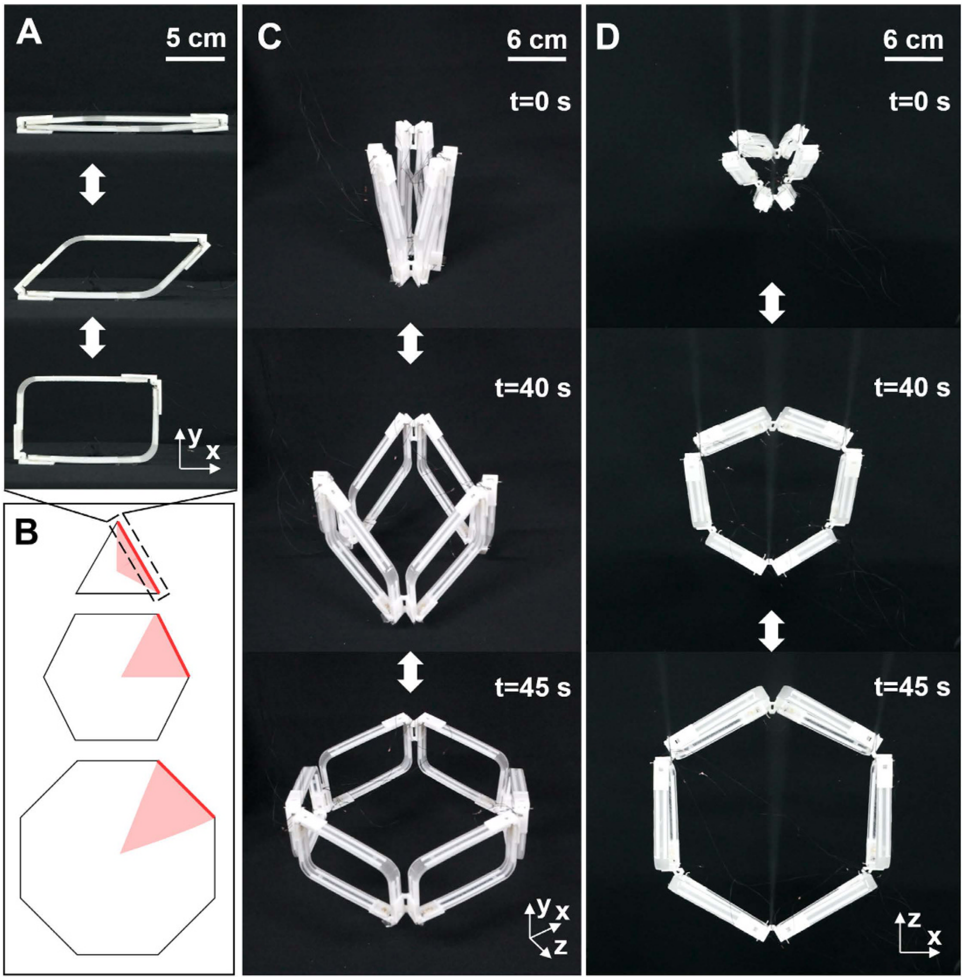

Figure 6. Deploying processes of quadrilateral single-loop module and its assembly. (**A**) Deploying process of a quadrangular module from a compact folded state to a fully deployed state. (**B**) Schematic of the deployed shape of ring deployable structures with three, six and eight edges. (**C**) Oblique view and (**D**) top view of deploying process of an extended six-edge ring structure composed of six basic quadrangular modules.

blue are used to create tension to unfold the reflective structure during deployments and the cables in orange are used to pull down and fold the center of the reflective surface during folding. The deployable mirror structure is fabricated and its deploying process is tested (Fig. 7B–C; Supplementary Video S5). To verify the effect of the light reflection, the deployable mirror is used to reflect the sunlight onto a small-scale solar panel (50 × 60 mm) located in a shelter without direct access to sunlight (Fig. 7D). A light-emitting diode (LED) in a sealed aluminum tube was connected to the small-scale solar panel for verification of the viability of the proposed structure. When the sunlight is reflected to the solar panel, the intensity of the LED is increased significantly (Fig. 7E; Supplementary Fig. S4). Without the sunlight being reflected onto the solar panel, the voltage and current outputted to the LED were measured to be 1.90 V and 2.24 mA, and the small-scale solar panel generated a power of 4.26 mW. With reflected sunlight to the solar panel, the working voltage and working current for the LED measured to be 2.05 V and 8.31 mA, and the small-scale solar panel generated a power of 17 mW with an increased power ratio of 4.

Conclusion

In this work, a simple manufacturing method for SSC actuators was demonstrated that enables the fabrication of a soft hinge actuator with variable stiffness properties by combining a soft matrix with a rigid skeleton and a variable stiffness segment making use of strategic placement of fusible alloy material. Thermal effect is used to change the state of the variable stiffness segment with the bending modulus of the actuator structure in the high stiffness being equal to 137.08 MPa and in low stiffness state equal to 3.47 MPa, which corresponds to a ratio of the modulus of approximately 39.5. SMA wires are used to realize the deformation of the structure in the low stiffness state and to maintain the deformation during cooling of the variable stiffness structures in order to maintain the desired configuration without further energy consumption.

The described hinge actuators are capable of variable stiffness and continuous morphing, and can be used to construct deployable structures based on three principles: design of basic hinge actuators, assembly of modules and assembly of modules into large-scale deployable structures. This study focuses on two types of structures

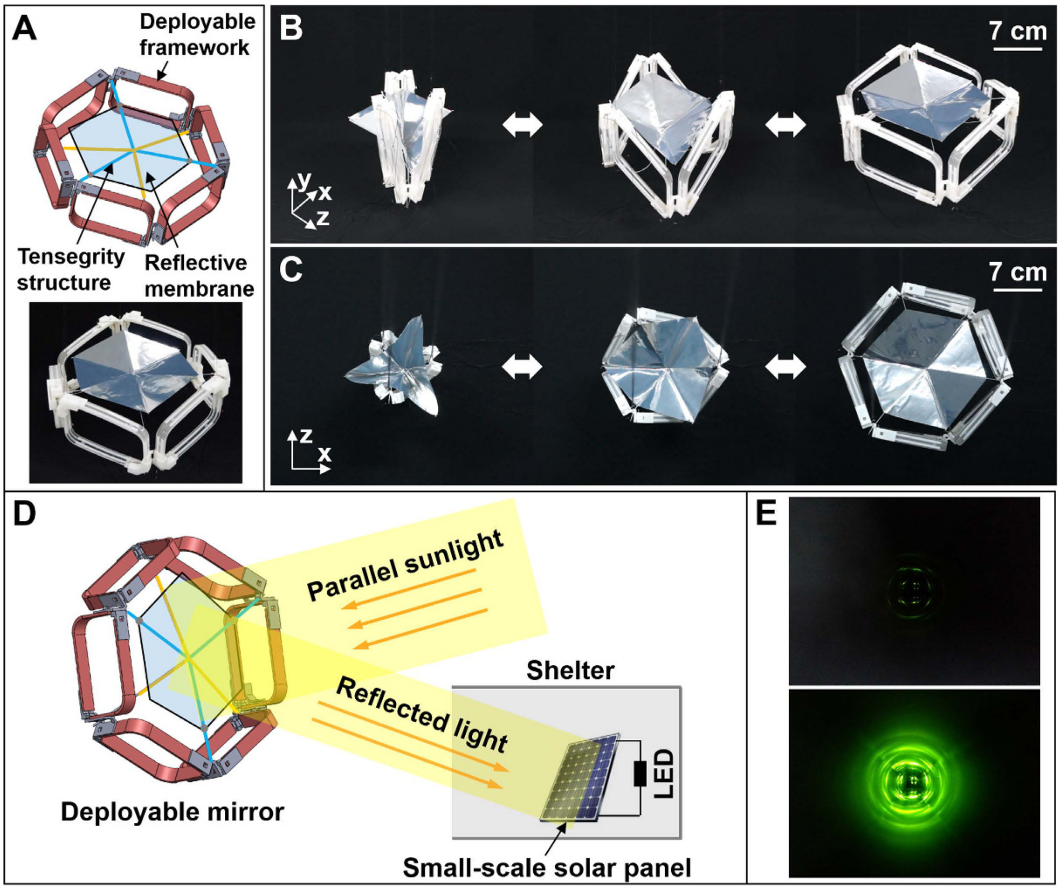

Figure 7. Fabricated deployable mirror and evaluation of its performance. (**A**) Schematics of the components to form a deployable mirror and the fabricated prototype. (**B–C**) Oblique view and top down view of deploying process of the deployable mirror. (**D**) Schematic of the experimental setup to test the deployable mirror reflecting sunlight onto a small-scale solar panel located in a covered shelter. (**E**) The LED before and after the deployment of the deployable mirror to reflect sunlight onto the solar panel.

often used in aerospace applications: deployable masts and deployable reflectors. The design of a triangular mast was first proposed through using three basic hinge actuators to form a module and using three superposed modules to build the deployable mast structure capable of deploying at a height of 4.6 times its folded height. However, the deformation required to fully recover the deformation of the actuator in the mast is larger than that which the hinge actuator can provide such that this module has to be reset manually to repeat the experiment. Then, single-loop modules were built using two basic hinge actuators in order to reduce the required range of actuation of the actuator and enable the fabrication of modules capable of both unfolding and folding deformations. This single-loop module has a lower range of actuation and can thus recover its deformation by itself for repeated deployment. Then, the single-loop modules were used to build a planar deployable structure for large one-dimensional deployable applications and a ring deployable structure for large two-dimensional deployable applications. The planar deployable structure is capable of an expansion ratio of 5 in height and the ring deployable structure of an expansion ratio of 8 in area. It is worth mentioning that the proposed modules are not limited to the suggested deployable structures and could be used to form different types of deployable structures. Moreover, it should be pointed out that deployable modules and structures are not limited to using a single type of actuator or module and can be made by using different combinations of actuators, modules and structures. A deployable mirror was finally fabricated by attaching a reflective membrane to the developed ring deployable structure using tensegrity structure and its functionality was tested.

The main contributions of this work are the design and manufacturing of a soft actuator usable in deployable structures by combining both hinge-like motion and shape retention capability, the framework from actuator to module and module to structure for the development of SMA-based deployable structures, and the specific design of the proposed modules and structures. The proposed structures have been tested multiple times each, but more experiments would be required to determine their service life and would require further rigorous testing to determine whether modifications have to be made for the proposed design to be usable in a wide range of applications. Further works will focus on the precision of the deploying process, improvement of reliability, optimized design of structure and assembling methods for larger scale deployable structure with flat or even curved shapes. Moreover, because of the sensing capability of smart actuators, it is also possible to integrate functional electronic components into the deployable structure to form a single integrated system capable of perform remote sensing, communication and that is energitically self-sufficient.

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Author Contributions

W.W. and S.H.A. conceived and designed the study. W.W. performed the experiments. W.W. and H.R. analyzed the results. W.W., H.R. and S.H.A wrote the paper and all authors commented on the paper.

Additional Information

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