Self-Folding Shape Memory Laminates for Automated Fabrication*

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Abstract— **Nature regularly uses self-folding as an efficient approach to automated fabrication. In engineered systems, however, the use of self-folding has been primarily restricted to the assembly of small structures using exotic materials and/or complex infrastructures. In this paper we present three approaches to the self-folding of structures using low-cost, rapid-prototyped shape memory laminates. These structures require minimal deployment infrastructure, and are activated by light, heat, or electricity. We compare the fabrication of a fundamental structure (a cube) using each approach, and test ways to control fold angles in each case. Finally, for each self-folding approach we present a unique structure that the approach is particularly suited to fold, and discuss the advantages and disadvantages of each approach.**

I. INTRODUCTION

Engineered systems are typically manufactured using complex 3-D fabrication and assembly processes that are expensive and time consuming. Additionally, complicated infrastructures are usually required for the assembly of these systems. Nature, by contrast, has found an efficient approach to the fabrication of lightweight structures that require little or no infrastructure for deployment: self-folding.

Self-folding structures can be found in biology at length scales from nanometers to meters, such as organic molecules [1], winged insects [2], brains [3], and tree leaves [4], [5]. Self-folding automates the construction of arbitrarily complex geometries at arbitrarily large or small scales. Folding also has many advantages over traditional manufacturing methods, including reduced material consumption and creation of structures with improved strength-to-weight ratios. Folded designs have found useful engineering applications in areas such as space exploration [6] and logistics [7]. Complimentary theoretical work has proven that folding is in fact capable of achieving a large set of target geometries [8], [9], [10]. Recently, origami inspired folding has also enabled great strides in the fabrication of mm to cm scale robotics [11], [12], [13]. However, fold actuation remains a challenge as these robots often require many hours and/or microsurgeon dexterity to assemble manually. Reliable self-folding techniques would be a boon to automated fabrication of folded devices, as well as to self-deployable systems.

Research in small-scale fabrication has developed a variety of self-folding mechanisms. One approach folded lithographically patterned thin films spontaneously via residual stress [14], while another folded hydrogel composites with differential swelling when exposed to water [15]. Layered composites have been shown to self-fold when exposed to a change in pH, temperature, or the addition of a solvent [16]. Self-folding mesoscale structures have been activated by lasers and magnetic fields [17], [18], and complex machines have been assembled via Pop-Up MEMS [19], [20]. In focusing on how to fold structures too small to be directly manipulated in an accurate way, these previous approaches have employed expensive tools and materials, and in many cases used complex infrastructure for deployment (such as lasers and magnetic fields).

At the centimeter scale, we have previously used shape memory alloys to actuate a self-folding sheet of programmable matter [21]. In designing a universal sheet capable of folding into any shape, this approach relied on the use of complex materials and fabrication approaches, and would not be efficient in the assembly of specific target structures. Recent work has employed selective light absorption to cause inexpensive, single-use shape memory polymers (SMPs) to self-fold into target structures[22]. While this is a simple and inexpensive approach to self-folding, the single-material approach limits the strength and potential applications of the structures formed. Recently, we have demonstrated the use of similar SMPs, selectively actuated by resistive heaters, to realize self-folding robots and structures [23], [24].

In this paper we compare three approaches to the fabrication and actuation of low-cost self-folding shape memory laminates. All of these approaches use inexpensive, single-use, heat activated SMPs for self-folding, but each produces the activating heat in a unique way. The first approach targets the heating of the SMP with selective light absorption, the second localizes SMP actuation using resistive heating elements, and the third achieves folding by uniform environmental heating, relying on mechanical design to control folding. For each approach we describe the design, fabrication, and self-folding of a common fundamental structural building block (a cube), as well as unique structure to which the approach is particularly well suited to assemble. We also present experimental results in controlling fold angles, and compare and contrast the advantages and disadvantages of each approach.

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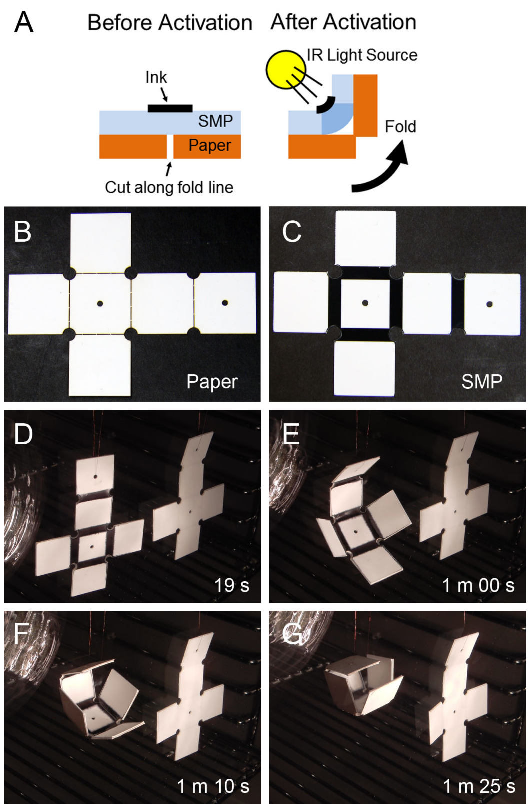

Fig. 1. Light activated self folding of a 20 mm long cube. A) Cross section schematic of light activated folding. B) Paperboard and C) SMP layers compose a two-piece laminate. Black lines of ink are printed directly onto the SMP prior to laser machining. D-G) Frames from experiment in which two laminates, one with ink and one without, were introduced into an oven preheated to 90°C. An infrared light was shone through the front glass of the oven. The printed black lines absorb enough light energy to locally activate the SMP.

II. Light Activated Folding

The basic principle employed in all of our self-folding laminates is akin to a unimorph actuator. In the simplest configuration, a contractile layer is bonded to a mechanical layer. When the contractile layer is activated (induced to contract), the resulting stress cause the bimorph to bend. In order to localize this bending along a fold line, we weaken the mechanical layer at the desired fold location and localize the contraction of the contractile layer above the fold. When the activating heat source is removed, the contractile layer cools, maintains its deformed shape, and stiffens, holding the fold in place.

For light activated heating, black lines are used to preferentially absorb light energy from an infrared light source, localizing the heating of the material underneath (Fig. 1A). Without this localization, the contractile layer activates indiscriminately and tends to delaminate from the mechanical layer.

For our light activated folding experiments, we used 0.5 mm thick paperboard as a mechanical layer (Fig. 1B) and 0.3 mm thick pre-strained polystyrene sheets (Grafix Inkjet Printable Shrink Film, Grafix) as our SMP layer

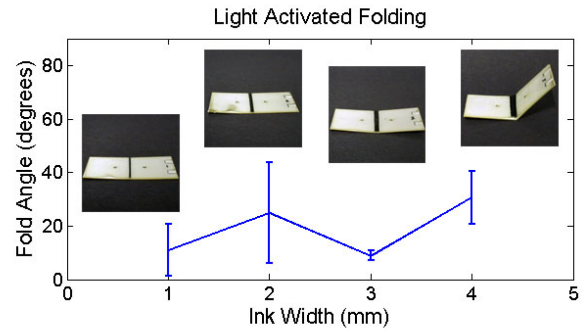

Fig. 2. Plot of fold angle versus ink line width for a single-fold test laminate. Error bars represent standard error across five samples for each width of ink. Representative samples are pictured above their respective data points.

(Fig. 1C). Our chosen SMP was commercially available, inexpensive, and had an activation temperature of 102.7°C [[22]], which is well above room temperature but below the flash point of paperboard. We printed black ink directly onto the polystyrene sheets with a solid ink printer (ColorQube, Xerox; inkjet printers were also used successfully). We laser machined both materials with a CO2 laser machining system (VersaLaser, Universal Laser Systems). We aligned the two layers with pins and bonded them with 50 μm double-sided silicone tape (ARclad 7876, Adhesives Research).

As in [22], we found in necessary to pre-heat the SMP to a temperature below the activation temperature. Thus, we suspended the laminates facing the front of an oven preheated to 90°C, and shone an infrared light in through the glass door (Fig. 1D-G). We also suspended an identical laminate without black lines along the hinges in order to verify that it was necessary to localize the light absorption. We observed folding in both cases, although it was much more pronounced and much more regular with ink printed along the hinges (Fig. 1G, supp. movie).

A significant challenge with self-folding is achieving controllable fold angles. We hypothesized that thicker ink lines would result in larger fold angles. In order to test this effect, we printed single-fold laminates measuring 62 mm by 32 mm with ink lines of thicknesses varying from 1 to 4 mm (Fig. 2). In this case, we pre-heated the laminates on a hot plate (pre-heating on a hot plate was effective only for simple structures where all actuated folds stay in contact with the plate during folding). A 250 W infrared light was mounted 11 cm above the hot plate. Each sample was placed on the hot plate underneath the light for 45 s and then removed. We then took a cross-section photo of each sample and measured the resulting fold angle with image processing software (ImageJ). Each data point in Fig.2 represents the average fold angle of five samples with the same line thickness.

Because light activated folding is inhibited by occlusions, this approach is generally limited to the folding of structures with shallow angles low overall curvature. This constraint can be relaxed with a movable light source, however this

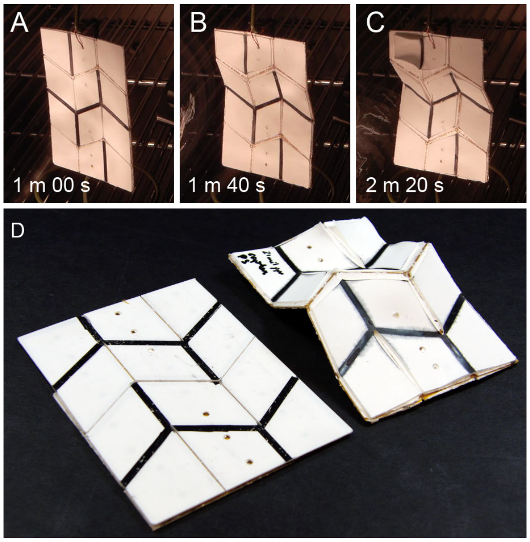

Fig. 3. Light activated Miura fold pattern. Black lines cause the SMP layer to contract, creating valley folds, while cuts in the SMP layer allow mountain folds. A-C) Frames from self-folding experiment with times indicated. D) Versions of the Miura fold laminate before and after light-activated folding.

requires additional deployment infrastructure. A strength of this approach, however, is the ability to actuate many folds simultaneously. The Miura fold pattern is thus well suited to this approach. The Miura fold is a regular pattern of folds that result in a single degree-of-freedom when the faces are treated as rigid bodies. It has been proposed as a way to efficiently pack solar panels [6]. With shallow folds it may be a way of improving structure rigidity or function with corrugation.

Following an approach similar to the cube example, we scored the crease pattern into a sheet of paperboard, and laminated on a sheet of SMP (Fig.3). Black lines on the SMP defined the valley folds, while the SMP was laser-cut along mountain folds to allow folding. The laminate was heated in an oven with light shone in through the front door. Light was applied for 140 s, at which point the sample had formed a Miura fold and was removed from the oven (see supp. movie).

III. Electrically Activated Folding

In order to localize SMP activation without relying on constraining external stimuli such as light, we explored the concept of generating the activating heat within the laminate itself. We achieved this by adding an electrical circuit layer to the laminate which contains resistive heating elements [23], [24]. An additional advantage of this approach is the ability to precisely control a structure's fold sequence. However, this comes at the cost of additional fabrication steps. Here we apply this approach to the self-folding of test structures for comparison with our other self-folding mechanisms.

We designed a self-folding cube laminate consisting of three layers: a mechanical paperboard layer, an electrical circuit layer, and an SMP layer (Fig. 4A-C). The electrical layer was custom fabricated by first printing a circuit mask

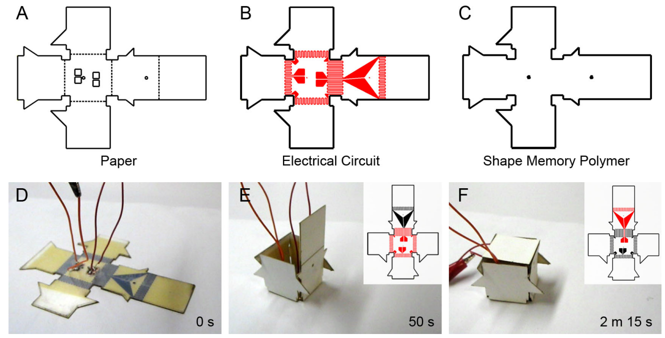

Fig. 4. Electrically activated self-folding cube. A-C) Designs of three layers that compose the electrically activated laminate: a paperboard mechanical layer (A), a copper clad polyimide electrical layer (B), and a pre-strained polystyrene shape memory polymer layer (C). D-F) Frames from self folding experiment. A power supply was used to run two amperes of current through the sub-circuits indicated in red on the insets. The time of each frame is indicated.

with solid ink onto a layer of copper-clad polyimide. The exposed copper was the etched in a heated copper chloride etch. Finally, the circuit was laser machined, pin-aligned, and bonded to the other layers with silicone tape. The flat laminate can be seen in Fig. 4D. Fig. 4E shows the cube after actuation of the four folds surrounding the bottom face with the resistive heaters highlighted in red in the inset. Due to small differences in actuation rates, some manual intervention was required at this step to prevent these walls from blocking one another (see supp. movie). The circuit indicated in Fig. 4F is then used to actuate the remaining fold as shown.

As with light activated folding, we used single fold samples to test the possibility of controlling fold angles during self-folding. While we have previously achieved some angle control by varying the overall width of the resistive heating elements [23], [24], we also found the heating duration to be important. Thus, here we fixed the heating element width at six millimeters (which simplifies design) and controlled the fold angle by adjusting the duration of current application. We applied two amperes of current for 30, 40, 50, or 60 s, and measured the resulting angle as before. We repeated this five times for each case. The results are shown in Fig. 5.

Electrically activated heating is well suited to the folding of structures or devices with minimal infrastructure required (i.e. an electrical power supply). Functional devices are also a good match since there is already an electrical layer embedded in the laminate. Thus, for demonstration purposes we designed and fabricated a self-folding gripper mechanism (Fig. 6, supp. movie). Unactuated folds serve as active degrees of freedom in the folded structure. Strips of polimide fed through the hollow digits and a slot in the base of the gripper act as artificial tendons which can be pulled on to actuate the device.

IV. Uniformly Activated Folding

The third self-folding approach uses uniform environmental heating as stimulation. In order to prevent heating

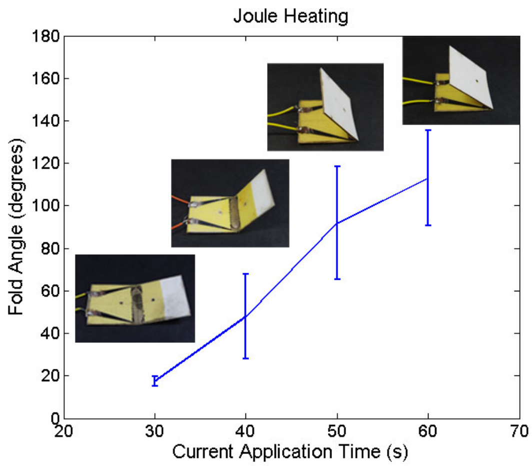

Fig. 5. Plot of fold angle versus current application time for a single-fold test laminate. Error bars represent standard error across five samples for each current application time. Representative samples are pictured above their respective data points.

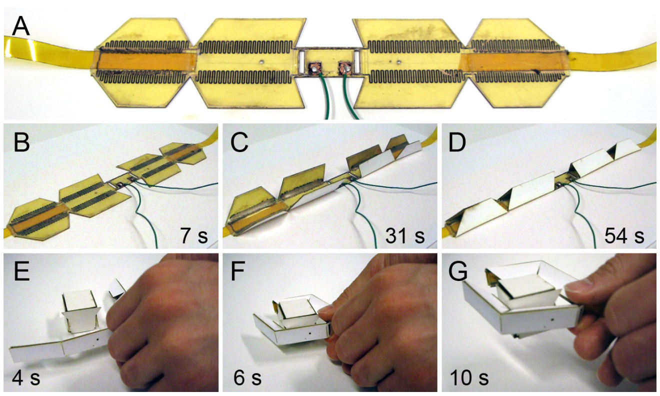

Fig. 6. Self-folding of a functional gripper. A) Self folding laminate with electrical heaters visible as black squarewave shaped lines along self-folding joints. B-D) Frames from self-folding experiment at room temperature. E-G) Frames from experiment demonstrating manual actuation of the gripper by pulling on artificial tendons woven through the digits.

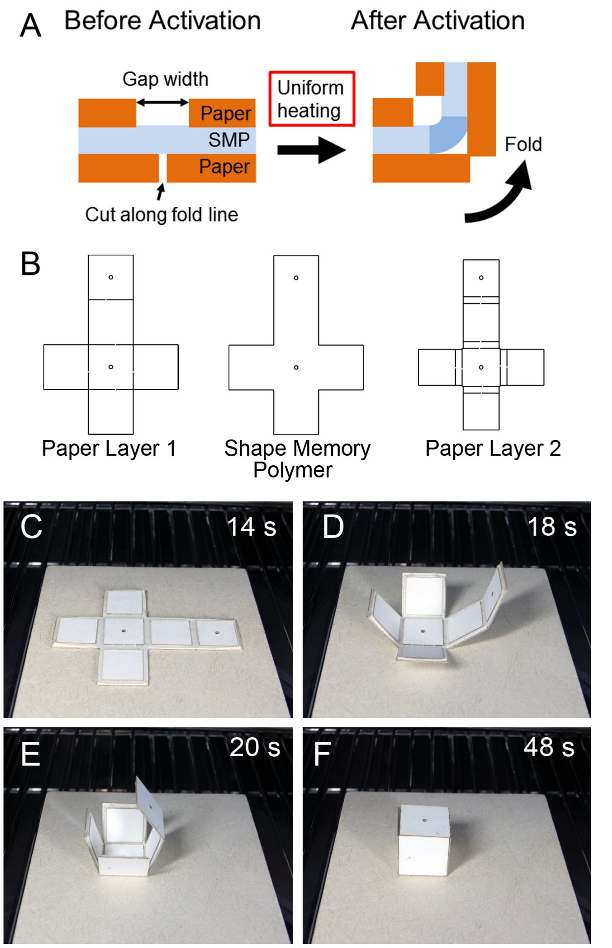

Fig. 7. Fabrication and self-folding of a 20 mm long cube structure with uniform heating. A) Cross-section schematic of the self-folding mechanism. B) bottom, middle, and top layers of the self-folding composite. The bottom and top layers are 0.5 mm thick paperboard, middle layer is 0.5 mm thick pre-strained polystyrene SMP. The three layers are stacked and adhered together with silicone adhesive film. C-F) Frames from a self-folding experiment in which the laminate was introduced into an oven preheated to 170°C. Also indicated are the time of each frame from the beginning of the experiment.

and contraction of the SMP layer at undesired locations away from the fold lines, a second mechanical layer of paper is added on top of the SMP. A gap of material cut out of this second layer allows the laminate to fold (Fig. 7A). Without this gap, the two mechanical layers constrain the SMP, preventing contraction even when activated, so deformation only occurs at the hinges. The result is structures that require very little intervention for assembly, or ”easy-bake” assembly.

One challenge with this approach is removing gaps of material on the second mechanical layer leaves islands of material that must be aligned properly during fabrication. We solved this problem by leaving a layer of sacrificial material connecting this islands that was removed manually after layer bonding. The designs of three layers of the uniform heating, self-folding cube are shown in (Fig. 7B). Once these layers were stacked and bonded together with silicone tape, the sacrificial strips between the paper squares on the inside of each cube face were removed manually, leaving the laminate seen in (Fig. 7C). This laminate was inserted into an oven pre-heated to 170°C, and folded into the target shape as shown in less than a minute (see supp. movie).

One interesting features of this uniform heating approach is that the second mechanical layer creates natural stops that limit the fold angle. To test if adjusting the internal gap widths could allow control over a wide range, we fabricated test laminates with a range of gap widths. Samples with gaps widths ranging from 1 to 11 mm were fabricated and inserted into an oven preheated to 170°C, and left until folding ended. The results, along with representative samples are shown in Fig. 8.

Since this uniform heating approach can actuate many folds simultaneously with minimal increase in fabrication complexity, this approach is well suited to the assembly of complex structures that can be assembled with many

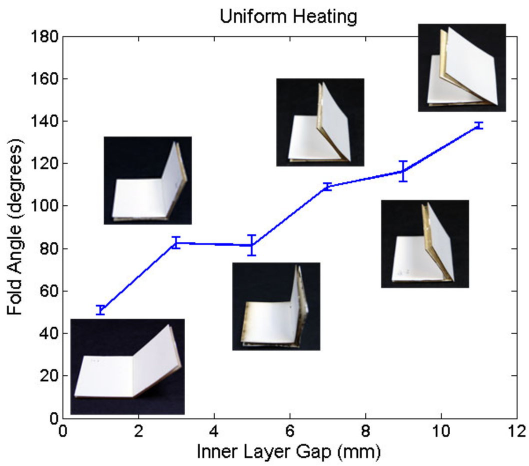

Fig. 8. Plot of fold angle versus the gap in the inner layer for a single-fold test laminate. Error bars represent standard error across five samples for each gap width. Representative samples are pictured above their respective data points.

simultaneous folds. As a demonstration, we fabricated a self-folding icosahedron with 19 actuated folds. Fig. 9 shows the three layers of the laminate, bonding of the three layers with pin alignment, and frames from the self-folding experiment. Based on the results of our angle study, an internal gap with of 1 mm was chosen to achieve a fold angles to match an icosahedron's dihedral angle of 138.2° as closely as possible. Material was also removed from the three-edge intersections to limit the interference of the edges near the vertices of the assembled structure. This structure self-folded in 1 m 04 s into the correct shape but with a gap (see supp. movie).

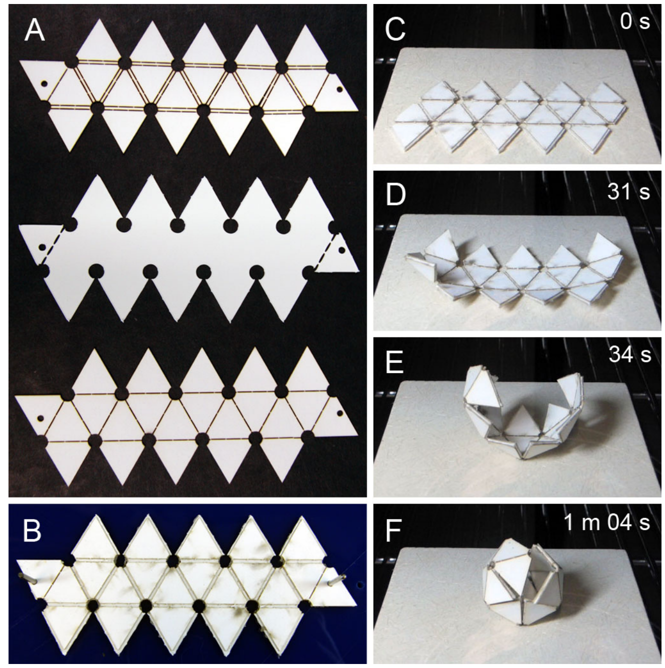

Fig. 9. Fabrication and self-folding of an icosahedron shape. A) Top-bottom: Inner paper layer, SMP layer, outer paper layer. B) Pin alignment is used for repeatable laminate alignment, layers are adhered with silicone tape, inner layer bridges are removed after layup. C-F) Frames from self-folding experiment in oven at 170°C with experimental time indicated.

V. Discussion

Based on the results of the previous three sections, we can draw some conclusions about the relative advantages and disadvantages of the three approaches to shape memory laminates for automated fabrication. Table I summarizes these results.

First, light activation was an intriguing method of directing self-folding, but difficult to implement in practice. Unlike a previous implementation of this approach [22], our laminates had to fold the additional weight of the mechanical layer, which we found necessary to add rigidity to the final structures. Due to occlusions, we found it difficult to achieve folds much beyond 90° without manipulation of the target or light source, which limits the usefulness of self-folding. Additionally, in our study of fold angles as a function of line widths, we found it very difficult to obtain consistent fold angles as the results were very sensitive to small perturbations in the experimental setup. Overall, we found light-activated folding to be most useful for the folding of structures with shallow angles and little structural curvature, such as the Miura pattern presented here. In this case, a single SMP layer actuated bidirectional folding, although only because of the single degree of freedom of the fold pattern. In general, an additional SMP layer would be required for bidirectional folding, as well as a second light source or a mechanism to rotate the piece.

Electrically activated heating was a consistent approach to self-assembly, although somewhat more complicated in fabrication. This approach had the significant advantage of achieving self-folding at room temperature. It achieved fold angles ranging from 20° to 120°. Our timed current delivery study found that these angles could be achieved somewhat consistently with simple temporal control of heating, although the range of the results indicates that alternative or complimentary angle control approaches would be desirable. Because of the capability of sequential actuation, this approach has the potential to achieve the assembly of structures that simultaneous folding methods cannot. The increased control over assembly, as well as the integration of electrical circuitry, mean this approach is well suited to the self-folding of functional devices such as grippers. In addition, we have previously demonstrated bidirectional folding with this approach with the addition of a second SMP layer [23], [24].

Finally, the uniform heating approach to self-folding shows a great deal of promise as a method that requires very little intervention post-fabrication. This means this approach may scale well both to the fabrication of large batches of structures and to structures with smaller dimensions. The cube fabricated using this method had very little error in side wall alignment. Our angle study in this case produced fairly consistent results which can be used in the design of self-folding structures such as the icosahedron presented

TABLE I

COMPARISON OF SELF-ASSEMBLY APPROACHES

Approach	**Light Activated Folding**	**Electrically Activated Folding**	**Uniformly Activated Folding**
Infrastructure required	oven and IR light	power supply	oven
Number of laminate layers	2[a]	3[b]	3
Cube assembly time	1 m 15 s	2 m 15 s	48 s
Cube completion	poor	good[c]	very good
Achievable angle range	0-40°	0-140°	0-140°
Angle repeatability	poor	good	very good
Sequential Folding	no	yes	no
Concave Structures	no	yes	yes

[a]In general, three layers required for bidirectional folding.
[b]Four layers required for bidirectional folding.
[c]Some manual assistance was required.

here. The final alignment of the icosahedron structure was not perfect, but could most likely be improved with design refinement. While it was not demonstrated here, it is expected that bidirectional folding could be achieved without any additional laminate layers (although sacrificial material would also have to be removed from the first paper layer). The main drawbacks of this approach are the requirement of an additional mechanical layer, and the inability to achieve sequential folding. One interesting possibility would be to alleviate this last disadvantage by combining the mechanical alignment of this approach with the electrical heaters of the previous one, gaining the strengths of both.

VI. CONCLUSIONS

In this paper we have presented three approaches to achieving self-folding with shape memory laminates for automated fabrication: one used light-activation, a second used resistive heaters, and a third used uniform heating with mechanical stops. We fabricated a common structure (a cube) using each approach, and tested approaches to controlling fold angles in each case. Finally, we demonstrated the strengths of each approach with a unique structure, and compared the advantages and disadvantages of each approach.

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