2013 IEEE International Conference on Robotics and Automation (ICRA)
Karlsruhe, Germany, May 6-10, 2013

# Robot Self-Assembly by Folding: A Printed Inchworm Robot

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*Abstract*— **Printing and folding are fast and inexpensive methods for prototyping complex machines. Self-assembly of the folding step would expand the possibilities of this method to include applications where external manipulation is costly, such as micro-assembly, mass production, and space applications. This paper presents a method for self-folding of printed robots from two-dimensional materials based on shape memory polymers actuated by joule heating using embedded circuits. This method was shown to be capable of sequential folding, angle-controlled folds, slot-and-tab assembly, and mountain and valley folds. An inchworm robot was designed to demonstrate the merits of this technique. Upon the application of sufficient current, the robot was able to fold into its functional form with fold angle deviations within six degrees. This printed robot demonstrated locomotion at a speed of two millimeters per second.**

## I. INTRODUCTION

Printable robots are a class of machines that are inexpensive, easy to design and manufacture, and amenable to rapid prototyping [1], [2]. These traits are achieved by the use of fabrication methods such as laser-machining, lithography, and pick-and-place circuit assembly. Each of these methods is nominally two-dimensional, necessitating a final transformation from two to three dimensions. To this end, folding has been utilized as a versatile and inexpensive technique to create complex three-dimensional machines from two-dimensional structures. By patterning two-dimensional materials and then assembling via folding, inexpensive robots can be rapidly designed, built, and tested.

Practiced for hundreds of years as the art of origami [3], folding has already been shown to be capable of a wide variety of geometries [4], [5], including any flat polygonal region [6] and any object consisting of cubes [7]. Because of this versatility of form and scale, it has been observed in biology from the organ to the molecular level [8], [9], [10]. Folding has also been demonstrated to have many uses in engineering, including paper actuators [11], springs [12], and programmable structures [13]. In addition to low cost, folding has logistical benefits, since structures are easier to store and transport in a planar form. This would be valuable in space applications [14] and commercial shipping [15].

Creating complex geometries and mechanisms by manual folding requires a significant amount of time and effort. Self-folding is therefore desirable to assemble three-dimensional

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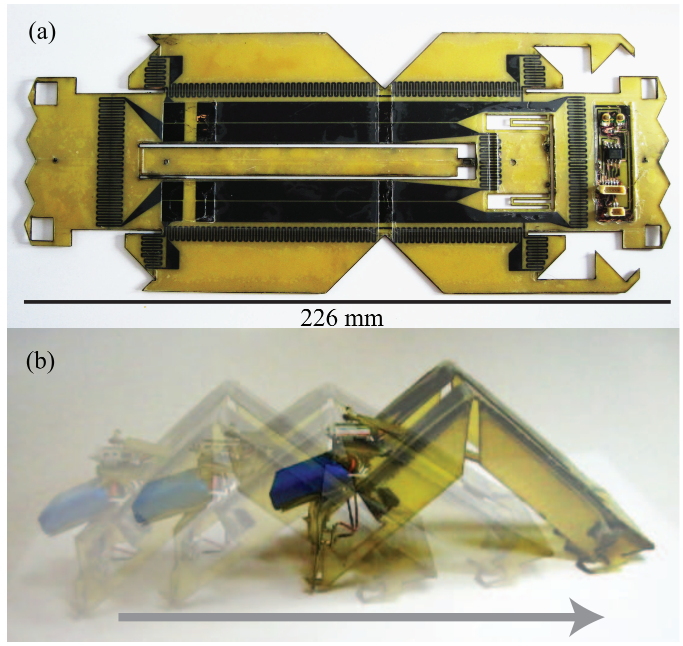


Fig. 1. (a) The two-dimensional inchworm robot, before it has folded into its functional shape. (b) The folded inchworm, after the servo and battery has been added. This robot weighs 29 g, and moves at a rate of 2 mm/s.

structures from two-dimensional materials without external manipulation. Self-folding is valuable when the operating scale is prohibitively small, or the cost of actuation is prohibitively expensive [16], and has been realized in a variety of ways. Magnetic fields have been used by embedding magnetic material into hinged microstructures to selectively actuate folds [17], [18]. A variety of micro- and nano-scale structures have been designed to self-assemble under uniform environmental cues due to polymer swelling [19], surface tension [20], or chemical triggers [21].

Shape memory materials (SMMs) are another approach to hinge actuation that have demonstrated self-assembling mechanisms in three ways [22], [23], [24]. The simplest method is to pre-program the final conformation into the 'memory' of the material; the SMM will morph into this conformation under uniform heating [25]. This method still requires three-dimensional fabrication techniques during the programming, but can allow for easier transportation and storage. The second is to use SMMs as hinges attached to a passive wall [13], [26]. These can be activated with a local or uniform stimulus, but the fabrication of these composites is more complex; the hinges must be manufactured separately, and then integrated into the passive composite.

Finally, SMMs have been used that undergo uniform

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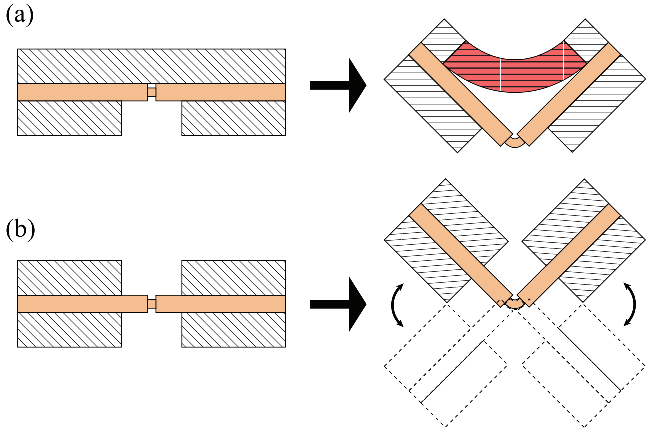


Fig. 2. (a) Structural bending occurs when a contractile layer is bonded to a passive substrate. Folding will occur where the substrate has been weakened. (b) Dynamic folds are necessary for articulation of a folded device. This fold is created by weakening the substrate and removing the contractile layer from both sides.

compression, but have features which localize the effect of a uniform stimulus. Polyimide has been used to fold microstructures [27] by micropatterning hinges. Prestretched polystyrene (PSPS) is a promising option for self-folding applications because of its low cost and ease of activation. Commercially known as "Shrinky-dinks", it is a prestretched polymer that exhibits 50% compressive in-plane strain when heated to 160°C. It has been used to create shapes that exhibit precise self-folds, as well as mountain and valley folding, when exposed to light [28]. By printing black ink along the hinges, the PSPS absorbs more energy from light along these lines, causing localized actuation.

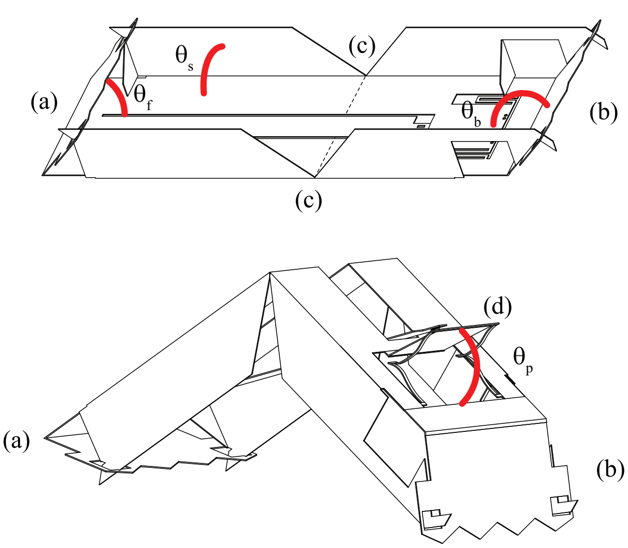


Fig. 3. The inchworm robot consists of a front wall (a) and back wall (b) angled to create 'feet' with asymmetric friction. The front wall fold angle $\theta_f$ is 45° and the back wall fold angle $\theta_b$ is 135°. The robot also includes side walls (c) with fold angles, $\theta_s$, of 90°, and a servo platform (d) with a fold angle, $\theta_p$, of 45°. The top image represents the inchworm robot after the folding of its front, back, and side walls. The bottom image represents an upright and completely folded inchworm.

From these examples, and considering the range of structures we are interested in creating, we identify four principle requirements for a viable self-folding method: (I) sequential folding, (II) angle-controlled folds, (III) slot-and-tab assembly, and (IV) mountain-valley folding. In order to accomplish all four, we needed a new self-folding method based on activation from a localized and independent stimulus. This paper presents a novel technique for self-folding that utilizes shape memory polymers, resistive circuits, and structural design features to achieve these requirements and create two-dimensional composites capable of self-folding into three-dimensional devices. To demonstrate these techniques, we describe the development of the inchworm robot shown in Fig. 1.

## II. DESIGN AND FABRICATION

Self-folding robots require both one-time, rigid folds to create the structure of the robot and flexible, dynamic folds for movement. The mechanism developed for the structural folds comprises two active contractile layers bonded to either side of a passive substrate. A unidirectional hinge is created by removing a strip of contractile material from one side. When the opposite contractile layer is activated, the hinge folds (Fig. 2a). Dynamic hinges are created by removing strips of the contractile layer from both sides, allowing the substrate to bend freely (Fig. 2b). In both cases, the hinge is perforated to make bending easier and to enable precise folds. A fourth layer is used to locally activate the contractile component, enabling sequential and simultaneous folding. This layer consists of copper traces and utilizes joule-heating to activate the folds. This layer also contains the electronics to power and control the robot.

### A. Inchworm Design

In order to demonstrate self-folding, a design was chosen that incorporates the four requirements listed above: the inchworm robot shown in Fig. 1. Locomotion is achieved by angling the 'feet' at the bottom of the front and back walls (Fig. 3a-b) to create asymmetric friction. The front wall fold angle relative to the robot body is 45° and the back wall fold angle is 135°. Side walls (Fig. 3c) are included at right angles to the robot body to improve structural rigidity. A single dynamic hinge in the middle is controlled by a slider-crank mechanism actuated by a linear servo. The servo is driven by a 0.3 Hz triangle wave from a microcontroller (ATtiny13, Atmel), and powered by a 7.4 V lithium polymer battery (EFLB1202S20, E-flite). The servo is mounted on a platform that folds up 45° from the body (Fig. 3d).

### B. Materials

Materials were chosen for their physical properties, cost, and ease of use. A 125 $\mu$m thick sheet of Polyetheretherketone (PEEK) (APTIV 1000, Victrex) is used as the passive substrate due to its high flexural strength (163 MPa) and resistance to fatigue along folds. Prestretched polystyrene (PSPS) (KSF50-CIJ, Grafix) was chosen for the contractile layer due to its high compressive strains (50%) when heated

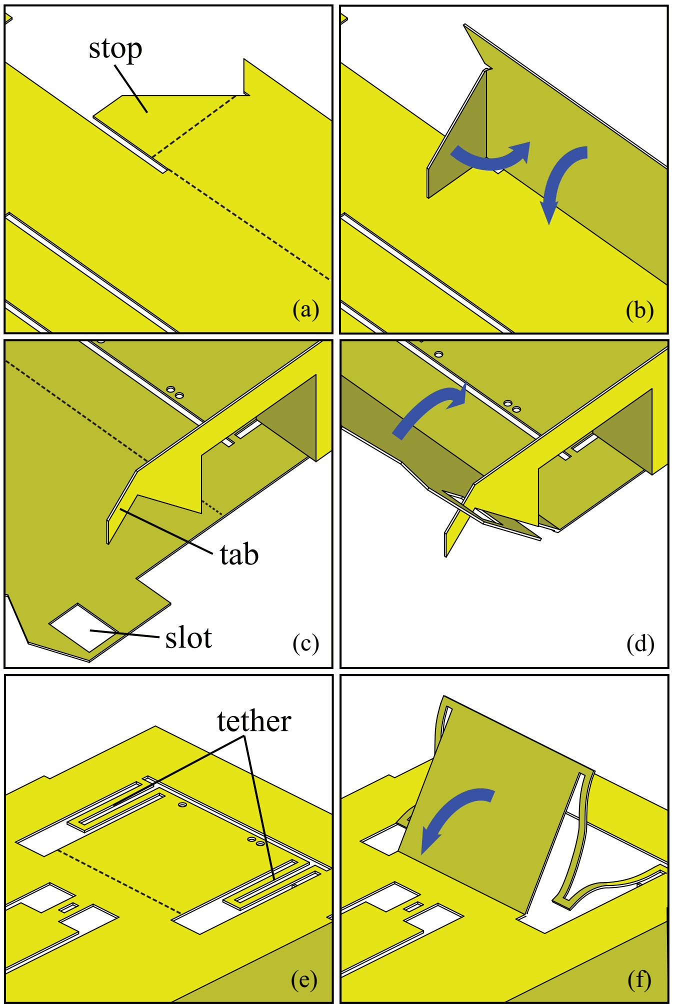


Fig. 4. In order to limit fold angles, stops were included in the design. (a-b) Initial stops were designed to fold simultaneously with the side walls. These stops would create a 90° angle in the wall fold, regardless of the angle of the stop's fold. (c-d) The front and back walls were designed to fold after the side walls. Slots were included in the front and back walls to align with tabs on the side walls. (e-f) The servo platform was limited by tethers cut in the PEEK layer. These tethers would not fully extend, but instead acted like springs that resist the actuated fold.

above its relatively low transition temperature (160°C) [28]. The circuits are made on a composite consisting of an 18 $\mu$m copper layer and a 12 $\mu$m sheet of polyimide.

### C. Folds

One challenge of self-folding is achieving precise folds without human observation and intervention. Effecting accurate and repeatable fold angles through hinge design alone would require more precise fabrication and materials with tighter tolerances; instead we rely on mechanical stops to physically limit the fold angle. To this end, most edges are folded sequentially, so that successive folds can align to previous ones. However, the initial side-wall folds include a triangular tab at one end, with a smaller fold running perpendicular to the desired folding edge. This activates simultaneously with the primary hinge, and acts as a mechanical stop for the primary fold, producing a right angle (Fig. 4a-b). Because of its geometry, this stop fold is tolerant of a large range of angles. Front and back walls fold next, and their angles are limited by the side walls. Tabs are included at the edge of each side wall, and slots in the front and back walls align to further control the geometry (Fig. 4c-d). The servo platform folds in the reverse direction; its angle is controlled by serpentine tethers cut into the PEEK layer (Fig. 4e-f). These tethers do not fully extend, but instead act like springs against the platform's hinge torque. The necessary length for constricting the platform to 45° was found experimentally.

Additional features were added to each layer to enable reliable folding (Fig. 2): at each fold, a 1 mm thick slot was cut into the PSPS on the convex edge to allow for easier folding and prevent opposing contraction; the PEEK at each fold was perforated to create a distinct hinge; Additional PSPS from the concave side was removed along the edges where traces could not be fit. These features are expressed on single layers only, and can be seen in Fig. 5.

### D. Heating Circuit

In order to achieve local and sequential folding, we required a way to activate the PSPS with a local stimulus. We used joule heating from resistive circuit traces because

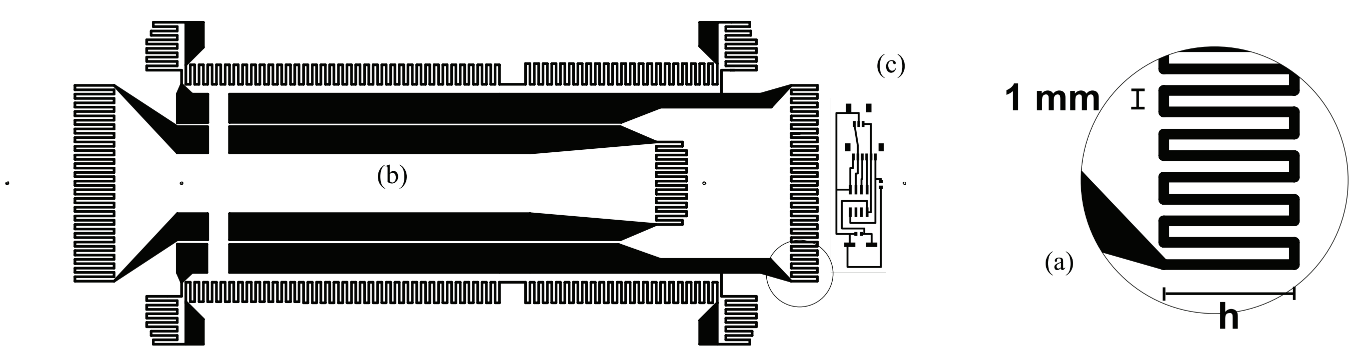


Fig. 5. The copper-polyimide layer consists of two independent circuits: the fold-activating heating circuit, and the servo control circuit. (a) The bulk of the layer is a collection of resistive circuits patterned to maximize the current path in order to produce and distribute heat. The traces are 0.5 mm thick, with a peak-to-peak height varying from 4.5 to 8 mm. (b) Portions of the activating circuit designed to carry current without producing heat were made as wide as possible to reduce resistance, preventing unintended heating. (c) The trace of the circuit used to drive the servo.

of the ease of patterning the copper-polyimide circuit with standard lithography and etching techniques, and due to its compatibility with our layered fabrication approach. The heat generated by a resistor is proportional to $I^2R$–where $I$ is the current and $R$ is the resistance–and $R$ is inversely proportional to the trace cross-sectional area. In order to generate sufficient heat with a reasonable current, the traces were made 0.5 mm wide, the lower limit of our copper etching technique. A serpentine trace pattern was used that increased the resistance and distributed the heat over a larger area. Both the peak-to-peak trace height and the fold geometry affected the current necessary to activate folding. Therefore, for each hinge, the trace height was determined empirically to ensure sufficient folding without excessive warping or peeling. Along non-heating portions, the trace width was made as wide as possible (under geometric constraints) in order to minimize unwanted heating and deformation. When possible, traces shared non-heating paths in order to simplify the circuit design. The complete trace design can be seen in Fig. 5.

### *E. Fabrication*

Circuit boards were etched on copper-polyimide by first masking the copper with a solid-ink printer. The circuit design was printed directly on the copper in wax, and then etched in ferric chloride. Each layer (PEEK, circuit, and two layers of PSPS) were cut with layer-specific features using a commercial CO2 laser machining system (VLS2.3, Unversal Laser Systems). These layers were aligned with two pins and manually bonded with 50 $\mu$m silicone tape (ARclad 7876, Adhesives Research)(Fig. 6a-d). This composite was laser-cut again into the final shape to prevent misaligned edges (Fig. 6e). Wires and electronic components were then soldered on. The structure, pre-folding, weighed 17 g (Fig. 1a).

## III. RESULTS

Self-folding occurred with minimal human intervention (see Supp. Video): The folding process was induced by applying two amps for a fixed amount of time to a succession of leads; each mountain fold was activated for 60 s, and the valley fold was activated for 90 s (Fig. 7). Based on resistance measurements of the circuit, the folding process consumed 900 J. The robot was manually flipped before valley-folding. The inchworm assembled into the desired configuration by sequentially activating its folds, and successfully achieved both mountain and valley folds (Fig. 1b).

After completion of the folding process and manual addition of a servo and battery, the inchworm robot weighed 29 g and measured 145 mm in its extended position. The robot was capable of moving on paper at a rate of 2 mm/s for a 0.3 Hz contraction frequency, or 0.8 body lengths per minute, and consumed 0.9 W during locomotion. Due to the complexity of asymmetric surface friction, this speed was irregular (Fig. 8). The stroke length of the foot displacement measured 10 mm; therefore only 20% of the motion was converted into locomotion, and the rest was lost to slippage. The contraction frequency was chosen because higher frequencies resulted in even more slippage.

Effectiveness of the angle-control techniques was evaluated by measuring the resulting angles of each fold (Fig. 3); over the three robots tested, the twelve sidewalls exhibited an angle $\theta_s$ on their tabbed edge of $88^\circ \pm 4^\circ$, compared to a planned angle of $90^\circ$; these side walls also exhibited angle variance along the wall length; farther from the mechanical stop on the tabbed edge, the walls folded farther inward. The front and back walls were more repeatable, likely due to stops at both ends. The back wall angle $\theta_b$ was $135^\circ \pm 1^\circ$ compared to a planned angle of $135^\circ$ and the front wall angle $\theta_f$ was $60^\circ \pm 3^\circ$, even though the mechanical limit of the fold was $45^\circ$. This systematic difference is likely due to an observed relaxation of the fold angle after activation. The tethers were a less accurate control method; the angle of the servo platform $\theta_p$ was $52^\circ \pm 10^\circ$, compared to a planned angle of $45^\circ$. The slot and tabs successfully aligned all twelve times.

## IV. DISCUSSION AND FUTURE WORK

The self-folding technique used here successfully demonstrated solutions to the four principle requirements for a self-

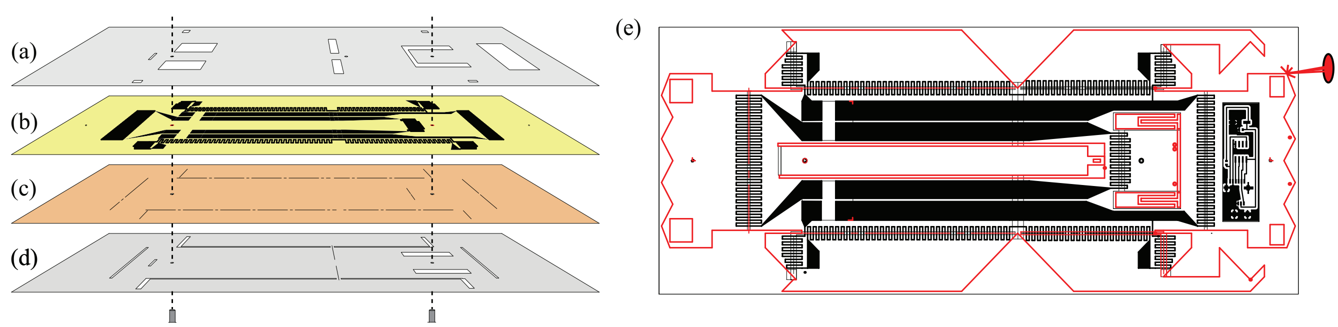


Fig. 6. The two-dimensional composite consists of four layers. Each layer was laser-cut separately, then pin-aligned and manually bonded with silicone tape. The final composite was laser-cut again into the desired shape. (a) A layer of PSPS activates mountain folds, including the side walls, front wall, and back wall. Windows are included to allow access to the circuits underneath, and slots are cut along valley fold seams to prevent antagonistic actuation. (b) The copper-polyimide layer is used to activate mountain and valley folding via joule heating. (c) The PEEK substrate is perforated along folding edges to enable easier and more precise folding. (d) A second layer of PSPS activates the valley fold, the servo platform. (e) The final composite is laser-cut again into the final two-dimensional shape.

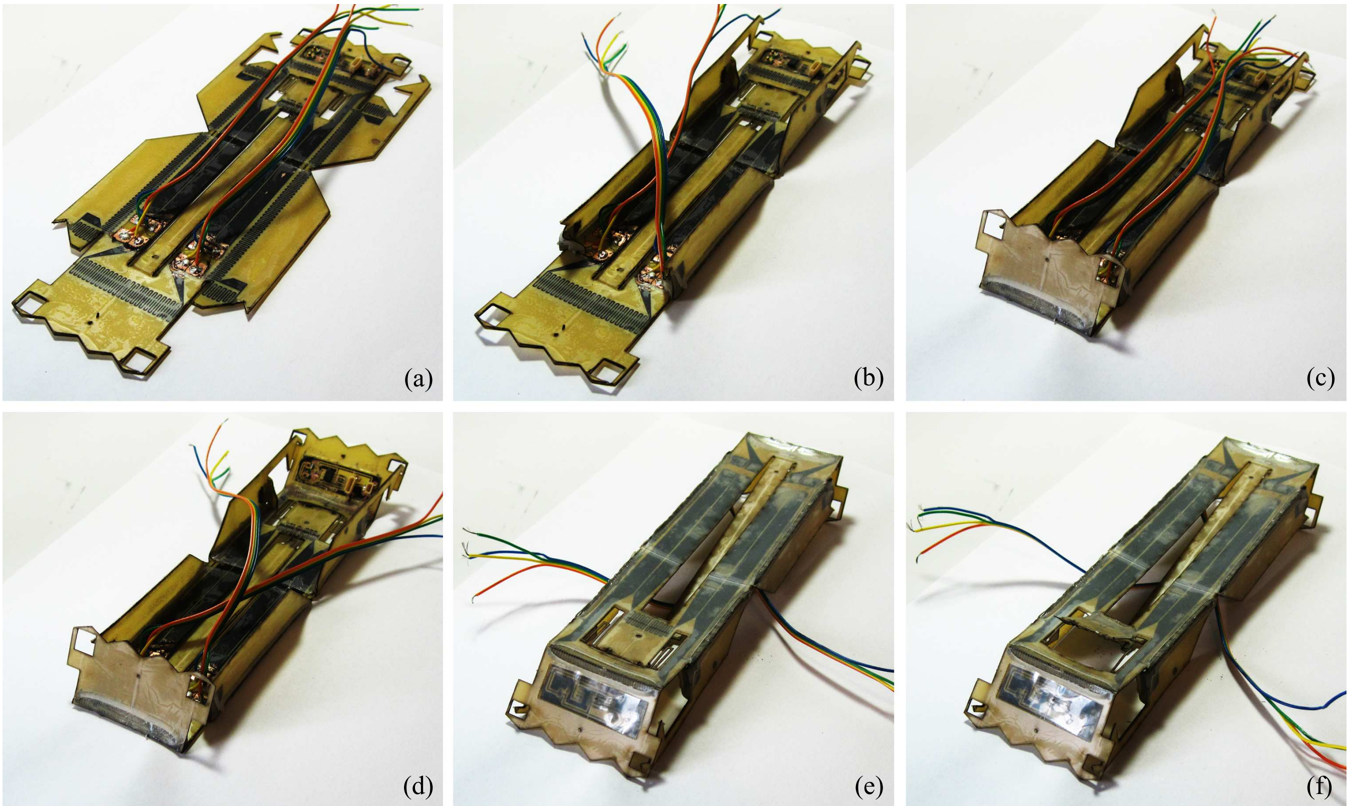


Fig. 7. Sequential folding of the inchworm robot. Each wall requires 2 A of current for 60 s, except for the servo platform, which takes 90 s. (a) The initial two-dimensional configuration. Sequentially folded are the side walls (b), the front wall (c) and the back wall (d). The inchworm is flipped over (e), and the servo platform folds (f).

folding robot. Sequential activation, mountain-valley folding, and slot-and-tab assembly were all demonstrated as designed. Mechanical stops proved adequate for angle control, but the technique would have to be improved for high-precision fabrication. The slight curvature observed along nominally flat surfaces might also be an issue for some other applications.

Angular precision could be achieved with feedback control; however, the sensors would need to be inexpensive and unobtrusive. An alternative way to increase precision would be to choose hinge parameters (such as trace size and material thickness) that would produce accurate fold angles without stops. Unfortunately, while the variables affecting folding speed and angle are easily observed, they are difficult to quantify. Upon activation, an area of PSPS undergoes a uniform stress, but the size of that area is affected by the continuing deformation of the composite. The substrate is also experiencing changes as it is heated, and the bonds between the three layers will often fail, further complicating an analytical model. However, even if the model couldn't predict an exact fold angle, it may be able to ensure that the hinge folded at a minimum to the mechanical stop. Such a model could be used to automate hinge design, and so would be a valuable tool for rapidly prototyping a wide range of machines.

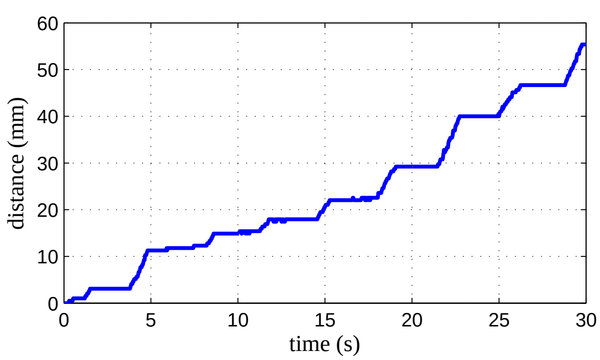


Fig. 8. The displacement of the front edge of the inchworm robot over time. The flat regions represent times when the inchworm is contracting. The irregular size of the steps demonstrates the unpredictability of asymmetric surface friction as a driving force.

The biggest obstacle towards achieving completely autonomous self-folding is insufficient hinge torque. The inchworm robot needed to be manually flipped because the actuated folds were not able to lift the body of the inchworm. Similarly, the servo and battery had to be attached after folding, because the hinges were incapable of lifting them. This is a universal problem; the center of mass of a three-dimensional machine will always be higher than a two-dimensional structure. Once the hinges are capable of lifting the weight of the body, a self-folding robot could transform from a planar structure to a fully operational machine without human intervention.

Future work will attempt to quantify and maximize the capabilities of this technique, in particular by testing new materials. PEEK and PSPS were chosen for their ease of use and low cost; other SMMs may provide stronger activation forces for tougher folds, and different substrates could provide stiffer walls.

## V. CONCLUSION

In this paper we have demonstrated a novel technique for self-folding using shape-memory polymers and resistive heating that is capable of several fabrication features: sequential folding, angle-controlled folds, slot-and-tab assembly, and mountain-valley folding. We used an inchworm robot to validate these techniques, which transformed itself from a two-dimensional composite to a three-dimensional functioning device via the application of current, a manual rotation, and the addition of a battery and servo.

This method can be applied to a large set of devices, is inexpensive and quick to fabricate, and requires few manual steps. It could be applied to structural prototyping to reduce material consumption and man-hours, or be used in an expeditionary environment where cost of transport is high, such as space or military deployment. With the addition of power and controls to the unfolded composite, it would be possible to build a robot that could deploy in its two-dimensional form, fold itself, and begin operations.

## ACKNOWLEDGMENT

The authors gratefully acknowledge support from the National Science Foundation (award numbers CCF-1138967 and EFRI-1240383). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

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