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APPLIED ORIGAMI

A method for building self-folding machines

S. Felton,[1]* M. Tolley,[1] E. Demaine,[2] D. Rus,[2] R. Wood[1]

Origami can turn a sheet of paper into complex three-dimensional shapes, and similar folding techniques can produce structures and mechanisms. To demonstrate the application of these techniques to the fabrication of machines, we developed a crawling robot that folds itself. The robot starts as a flat sheet with embedded electronics, and transforms autonomously into a functional machine. To accomplish this, we developed shape-memory composites that fold themselves along embedded hinges. We used these composites to recreate fundamental folded patterns, derived from computational origami, that can be extrapolated to a wide range of geometries and mechanisms. This origami-inspired robot can fold itself in 4 minutes and walk away without human intervention, demonstrating the potential both for complex self-folding machines and autonomous, self-controlled assembly.

Self-assembly is ubiquitous in nature, with examples as varied as the formation of cellular components (*1*) and dynamically organizing insect colonies (*2*). Self-assembly concepts drawn from natural contexts have many applications in engineering (*3*), and several artificial methods for self-assembly have been developed at length scales ranging from nanometers to centimeters (*4*). One particularly useful form of self-assembly involves folding two-dimensional materials into three-dimensional (3D) structures. Folding is capable of complex shapes and can be scaled to different sizes. Folded structures have high strength-to-weight ratios (*5*), and planar materials are compatible with a wide range of fabrication techniques (e.g., photolithography). Prior to folding, the integration of system components (e.g., batteries, integrated circuits, motors) can be automated for planar structures with the use of pick-and-place tools to populate printed circuit boards. Several actuation methods for self-folding have already been developed at a range of length scales from micrometers to centimeters, including polymer swelling (*6*), shape-memory materials (*7*, *8*), and magnetic fields (*9*). Fold patterns can be created using existing computational origami design automation tools (*10*–*13*), and many geometries and mechanisms have been invented that harness the unique strengths of folded structures (*14*–*16*). Existing approaches to self-folding are capable of creating static geometric structures but are limited in making complex geometries or functional mechanisms (i.e., structures that move or compute). Functional folded mechanisms have been demonstrated, but they require manual assembly steps, such as scaffold removal or integration of components after folding (*17*, *18*).

There are two primary application areas for a practical and sophisticated self-folding method. The first is remote, autonomous assembly. Structures and machines could be transported in a flat conformation, such as when putting satellites into space (*19*, *20*) or rapidly deploying shelters in dangerous environments (*21*, *22*). The second application is automation of certain aspects of manufacturing. In particular, self-folding can be combined with inexpensive planar fabrication techniques such as lithography, laser machining, and pick-and-place electrical component assembly machines to quickly produce machines from digital plans, allowing for "printable" manufacture (i.e., rapid manufacture with minimal overhead) to complement or compete with 3D printing, including the ability to create monolithic electromechanical systems (*23*).

We demonstrate that autonomous self-assembly of functional machines from flat sheets is possible with a composite that folds itself. Specifically, we used this composite to build a self-folding crawling robot that represents both a complex structure and a functional device that demonstrates three capabilities of the composite: (i) producing complex shapes, (ii) producing dynamic mechanisms, and (iii) assembling autonomously. The composite includes self-folding hinges that are controlled by embedded heating elements. The placement of these hinges in the composite and the order

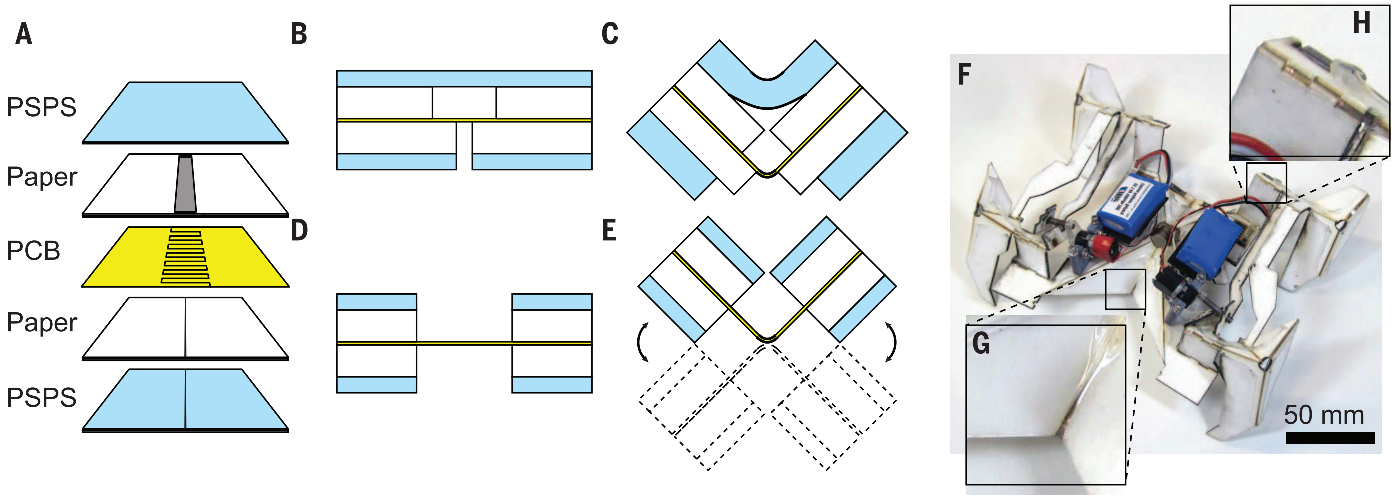

Fig. 1. Self-folding shape-memory composites. (**A**) The self-folding shape-memory composite consists of five layers: two outer layers of PSPS, two layers of paper, and a layer of polyimide (PCB) bearing a copper circuit in the middle. Cutting a gap into the upper paper layer allows controlled folding of the polyimide, and slits in the bottom layers of paper and PSPS prevent antagonistic forces. (**B**) A structural hinge, designed to fold once when activated and then become static. (**C**) When activated, the PSPS on the concave side pulls the two faces together, bending the polyimide along the hinge. (**D** and **E**) A dynamic hinge, designed to bend freely and repeatably. (**F**) A self-folding crawler built with the shape-memory composite. This robot includes both (**G**) self-folding and (**H**) dynamic hinges.

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in which they are triggered create a fold pattern that determines the final shape of the 3D structure or mechanism.

The self-folding composite combines a contractile layer of prestretched polystyrene (PSPS) and a passive paper substrate, resulting in a bimorph actuator (*24*). PSPS is a shape-memory polymer that is mechanically programmed to contract bidirectionally when heated to approximately 100°C. When the contractile layer is activated, it exerts a shear stress on the substrate, causing the composite to fold. These materials were chosen for their low cost and ease of use; substituting other shape-memory materials or substrates into the composite would be straightforward. Embedded resistive circuits are included at each hinge as heating elements to enable localized heating and activation of the PSPS. The composite includes PSPS on both sides to enable bidirectional folding (Fig. 1). Once folding is completed, the hinge is cooled and the PSPS hardens, resulting in a static fold. Self-folding hinges are programmed into the composite with layer-specific features (Fig. 1, B and C). Passive flexures for dynamic mechanisms are programmed in a similar manner (Fig. 1, D and E) (*25*). Not only are flexure joints compatible with folded assembly, they also have operational advantages over typical bearing joints, such as negligible friction losses and monolithic construction (*26*, *27*).

The composite's first capability is that of producing complex geometries. It is mathematically possible to fold arbitrary geometries from a single sheet of paper (*10*, *25*). In particular, Origamizer is a practical approach to design automation implemented as free software (*12*). To apply this algorithm to self-folding, we need to demonstrate two fundamental features of our composite: (i) the ability to fold a crease by an arbitrary angle in a desired direction, up to 180°, and (ii) the ability for these creases to be connected together in any cyclic fold—a collection of creases radiating outward from a point or area.

Previous work in shape-memory composites has already demonstrated folding of controlled angles of up to 135° (*24*, *28*), and angles up to 180° have been approximated using two adjacent folds (*29*). We control the fold angle by varying the gap width of the paper substrate at the hinge; the substrate acts as a mechanical stop, and a greater gap allows for a larger fold angle (fig. S2A) (*25*). Standalone hinges with square faces were built with varying paper gap widths to demonstrate that fold angles could be controlled via gap width. Each hinge was activated and allowed to fold to completion, at which point the hinge angle was measured. The data show that there is a positive correlation between gap width and fold angle over a range of 0° to 120°. The data also show that for a given gap width, the standard deviation of the final fold angle is 5° when the angle is less than 100°, and 8° when the angle is greater (fig. S2B).

The second feature necessary for complex geometries was demonstrated by including cyclic folds in the machine's fold pattern to create the body and the legs (Fig. 2, G and H). These folds provide stiffness and raise the robot's body while angling the legs downward. Furthermore, the legs are folded using a four-edge, single-vertex fold—a specific type of cyclic fold with a single degree of freedom. This fold is noteworthy because it is the component fold of the Miura pattern (*19*), a versatile fold pattern for compressing a large area into a small volume.

There is a limitation on the spatial resolution of a folded structure due to the thickness of the folded sheet. The algorithms mentioned above assume an infinitesimally thin material. Additional work developed rules and algorithms for so-called "thick origami" to account for the nonzero thickness of physical sheets (*30*).

The second capability of this composite is the ability to produce arbitrary mechanisms. It is mathematically possible to create bar-and-joint linkages that can trace any algebraic curve (*25*, *31*–*33*). To apply these results to self-folding, we need to produce general linkages with hinge joints. We demonstrate this by including two symmetric eight-bar linkages in the robot's design. Each linkage assembly is driven by one motor and actuates a front and back leg along trajectories designed to create a walking motion (Fig. 3). These linkages reduce the number of motors required for walking while enabling differential actuation for steering. We also demonstrate the ability to integrate motors with our linkages through alignment and locking tabs that couple the linkages to the motor crank arms (fig. S4).

The third capability of the composite, autonomous assembly, is demonstrated by the robot with embedded circuitry and an onboard power supply (fig. S5). Self-assembly occurs in five sequential steps controlled by an onboard microcontroller. Three of these steps involve actuated folding (Fig. 2).

The design was created using 2D computer design tools, so the digital plans are compatible with many software programs and fabrication tools. The robot was designed using a combination of kinematic simulations and iterative prototypes to determine a functional fold pattern. These rapid iterations were made possible by the fast fabrication process. (See supplementary text for additional design information for all components of the robot.)

Fabricating the 2D composite and installing the electrical components took 2 hours by hand (movie S2) (*34*). This is possible in part because the composite is 2D, allowing for easy installation and soldering. Our process was designed around readily available parts and materials, but the assembly time could be substantially reduced and completely automated with the use of pick-and-place electrical component assembly machines and automated adhesive dispensers.

The robot self-assembled in 270 s, after which time it was able to walk without further manual intervention (Fig. 2 and movie S1). The self-assembled linkage mechanisms operated effectively,

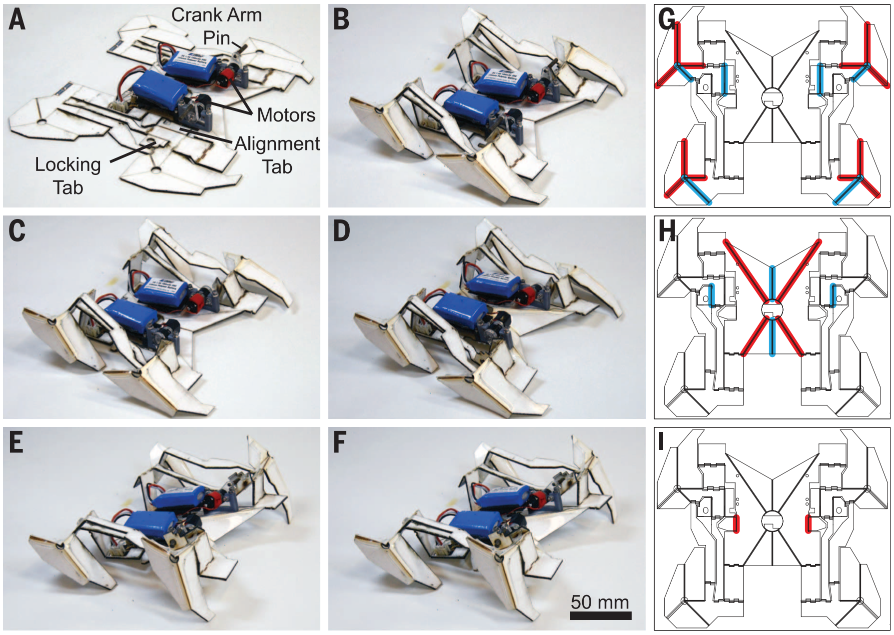

Fig. 2. The self-assembly steps of the robot. The robot assembles itself in five steps, three of which are self-folding. (A to F) The robot in each stage of assembly; (G to I) the fold pattern and active hinges. Activated mountain folds are highlighted in red, valley folds in blue. (**A**) The robot begins in a flat conformation. Folding is initiated 10 s after the batteries are connected. (**B** and **G**) The outer legs and alignment tabs fold first. As the legs fold, they bring the linkages into position. (**C**) The motors rotate 180°, pushing the crank arm pins into notches in the alignment tabs. (**D** and **H**) Next, the body and locking tabs fold. (**E**) The motors turn another 180°, causing the robot to stand up. (**F** and **I**) Smaller middle legs fold down for added stability. Once the final folds cool and become rigid, the robot is assembled and ready for operation.

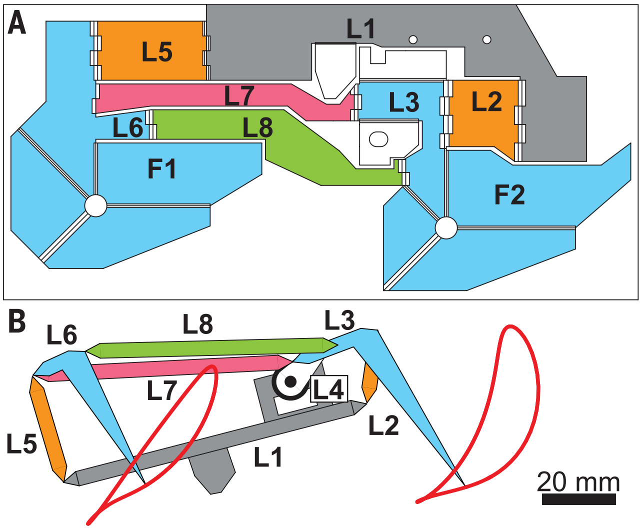

Fig. 3. Linkages connect the front and back legs to the motors of the self-folding robot. (**A**) The linkages before self-assembly takes place. (**B**) The linkage assembly after coupling with the motor. The front (right) leg is driven by a four-bar linkage (L1 to L4), and the rear (left) leg is driven by an eight-bar linkage (L1 to L8). The kinematics of the linkages produce walking trajectories in the front and rear feet when driven by the motors (shown in red). The middle leg (gray) supports the robot when the outer legs are raised. Linkage lengths are given in table S1.

demonstrating both the efficacy of the composite's dynamic hinges and its ability to precisely align folds to couple the motors to the linkages. When operating, the robot moved at a speed of 0.43 body lengths per second (5.4 cm/s). It was also able to turn at an average speed of 0.56 rad/s with an average turning radius of 6.1 cm. The folding process required approximately 8.8 kJ of electrical energy to activate (*25*).

We calculate that the mechanical work required to assemble the machine was 3.8 mJ, based on the mass (78 g) and final center of mass height (10 mm) of the machine. If we assume that the torque is exerted evenly by all hinges and that all hinges reach completion at 90°, then the total torque exerted by the hinges must be at least 0.01 N·m. This does not account for the effects of friction or antagonistic forces caused by hinges pushing against each other. According to an analytical model relating the hinge geometry and material properties to actuated torque, we calculate that the actual torque exerted by the hinges is 0.15 N·m (*25*).

Out of three attempted self-assemblies, one robot was able to complete the assembly process and achieve the desired functionality. In the other two trials, a single hinge failed to fold to the required precision. This illustrates the interdependent nature of self-assembling machines with localized actuation and the need for design methodologies that produce folding plans that are robust to failures of individual folds. If we consider these three trials as sets of individual hinges, 82 of 84 hinges self-folded to their necessary position (*25*).

For the machine presented here, folding was initiated by a simple timing program in the microcontroller, designed to trigger assembly 10 s after the batteries were connected. However, more complex triggers could be integrated, including wireless activation or response to an environmental change (*25*). The materials used in this robot are well suited for structures and machines at a length scale of tens of centimeters, but limitations imposed by fabrication techniques and hinge torques can restrict their use for smaller and larger devices, respectively. Fortunately, these limitations can be overcome by using different materials and fabrication methods. This substrate also has a maximum operating temperature of approximately 100°C. A higher temperature causes uniform activation of the shape-memory polymer, resulting in a deformed and nonfunctional machine. This limit can also be altered through material selection (*25*).

The self-folding robot demonstrates a practical process for creating self-assembling machines with complex structures and dynamics by means of planar materials and folding. By automating the folding process, origami-inspired machines can be produced without manual folding, reducing the skill and time necessary for fabrication. This technique can be used to rapidly prototype electromechanical systems, build satellites that assemble themselves in space, and fabricate centimeter-scale robots. Because this technique uses composites that are inexpensive and can be easily altered, this technique can be adapted to a wide range of applications.

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SUPPLEMENTARY MATERIALS

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