An Origami-Inspired Approach to Worm Robots

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***Abstract*—This paper presents an origami-inspired technique which allows the application of 2-D fabrication methods to build 3-D robotic systems. The ability to design robots as origami structures introduces a fast and low-cost fabrication method to modern, real-world robotic applications. We employ laser-machined origami patterns to build a new class of robotic systems for mobility and manipulation. Origami robots use only a flat sheet as the base structure for building complicated bodies. An arbitrarily complex folding pattern can be used to yield an array of functionalities, in the form of actuated hinges or active spring elements. For actuation, we use compact NiTi coil actuators placed on the body to move parts of the structure on-demand. We demonstrate, as a proof-of-concept case study, the end-to-end fabrication and assembly of a simple mobile robot that can undergo worm-like peristaltic locomotion.[1]**

***Index Terms*—Bioinspired robotics, origami-inspired robotics, peristaltic locomotion, printable robotics.**

I. Introduction

Today, the ever-increasing capabilities of robots are tightly constrained by limitations of their hardware. The bottleneck in the development rate of new robots with expanded capabilities in computation, mobility, and manipulation is the process of design, fabrication, assembly, and development of supporting hardware and electronics. To reduce this effect, we envision a fabrication technique that enables quantum advances in the way engineers develop robotic hardware with high speed and low cost in a straightforward procedure that links specifications to prototypes.

Recent advances in 3-D printing technologies provide one way to speed up the fabrication process in comparison to traditional machining practices. These machines deposit material in a layer-by-layer fashion using appropriate support materials that can be easily removed after the fact. It is becoming routine, especially in research laboratories to print various robot parts [2]. Almost any 3-D structure imaginable can be designed in a software tool and fabricated in this fashion.

On the other hand, many fabrication alternatives are available for planar substrates. Many of these processes were developed by the microfabrication industry and are directly useful to pattern sheets of a wide range of materials [3]. By a transformation method between the 2-D sheets and 3-D structures, robots can be built with even higher speeds and lower costs and deployed on demand. These robots also have the potential to be converted back to planar form for ease of storage and transportation.

This concept of fabricating a robot body on a planar sheet is similar to manufacturing a printable circuit board and especially flexible circuits. Instead of electrically wiring each component, a circuit board provides the traces and pads that form the body of the circuit and becomes operational upon population with components. Utilizing a printed circuit board (PCB)-type fabrication for robotics, a wider range of materials can be utilized and there already exists automated facilities, which could be updated to produce robot bodies and assemble components (e.g., sensors and actuators) on flat sheets.

To transform the patterned sheets into 3-D robots, many pieces can be individually fabricated and attached together. This, however, is a cumbersome process. A better alternative is to pattern a single sheet of material that can be folded into shape either manually or in an automated fashion. This way, motion generation elements can be embedded on the surfaces by special folds. Folding flat sheets into complex shapes is not a new concept, as it is the basis of origami; the traditional Japanese art. Recently, the power of origami has been discovered in the technical literature [3]–[9]. In this paper, we identify specific folding patterns that generate useful functionalities and use them as components in designing robots, as detailed in Section II.

Incorporating actuation into the otherwise passive origami mechanisms is the next step. To this end, we employ nickel titanium (NiTi) coil actuators that contract upon heating, which is accomplished by passing a current through the conductive actuator. These shape memory alloys (SMAs) have seen many applications in robotics for their useful properties [10], [11]. Because of their high achievable strain, high energy density, and compact size, these actuators are also ideal to operate origami-based robots by locally changing shape. Section II-B discusses these actuators and their application.

This paper addresses the general problem of making complete robotic systems with high speed and low cost starting from a flat sheet of material. To this goal, we propose a planar fabrication process to pattern foldable creases on the sheet, in order to achieve origami-inspired foldable structures. These structures are actuated by distributed NiTi coils during operation. The resulting robots can be stored and transported in planar form and folded into 3-D shape for deployment.

Compared to other robotic designs, an origami-inspired approach streamlines robotic fabrication. Structural and functional elements of the system can be placed on the body in planar form, and converted to 3-D by folding, without the need for assembly. This is especially relevant for the mesoscale, where assembly of

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Manuscript received November 1, 2011; revised March 22, 2012; accepted July 8, 2012. Date of publication August 13, 2012; date of current version January 10, 2013. Recommended by Guest Editor A. Ijspeert. This work was supported by the National Science Foundation Expeditions Program CCF-1138967.

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Digital Object Identifier 10.1109/TMECH.2012.2210239

[1] Some material in this paper has been adapted from [1].

small components require a lot of precision and manual effort. Another benefit of folded robots is their lightweight. With this approach, hollow polyhedral bodies can be produced as only the faces need to be solid, reducing the overall weight and material costs.

While the techniques proposed in this paper can be used to build a wide range of robots, Section III details the whole process of building a specific origami-inspired mobile robot that can undergo worm-like peristaltic locomotion. We describe the frictional properties required to generate forward motion, the design of a tubular body composed of a number of axial segments in series, controlling this robot with a custom PCB, and experimental results in this section.

The contributions of this paper are as follows:

1) development of a planar fabrication method that enables building origami-inspired robots by folding flat sheets of material into complex functional 3-D shapes;
2) distributed actuation of active crease patterns by compact NiTi coil spring actuators;
3) development of a mobile robot composed of multiple contractile segments in series to execute peristaltic locomotion, folded from a single sheet.

II. ORIGAMI-INSPIRED ROBOTS

Our main objective in this study is to develop and rapidly fabricate origami robot bodies by starting with a flat sheet of material. A suitable method to transform the fabricated planar sheets into their final 3-D shape is folding. This enables us to design and create every part of the robot body on a single sheet, eliminating complicated assembly requirements. Active elements such as hinges, joints, or springs can be placed on the body with ease using corresponding folding patterns on appropriate positions on the sheet.

The traditional Japanese art of origami provides us with the means to design foldable planar structures. Origami is fast becoming a technological tool. Computational origami is already a field of computer science with many practical applications [3], [5]. Computational tools are demonstrated that take a 3-D shape as input and return an appropriate crease pattern as output to generate the given shape when folded [12].

Moreover, some origami crease patterns have a property of universality [4], [5], [13]. This means that with a large enough sheet of paper, or small enough features, any 3-D structure can be sculpted. This result is for static shapes, but has the potential to be extended to functional structures. The field focusing on the creation of functional structures is *active origami*. Research in this field is aimed at creating structures or mechanisms that can create motion [8].

A basic set of origami folds can be arranged to arrive at an arbitrarily complicated design. This task, however, is not straightforward. The approach we take in our research is to identify certain folding patterns that combine form with functionality. This way, a special set of origami folds from a library are placed at the necessary positions to incorporate the corresponding action set. This is a level of abstraction that makes the design process more tractable. A sample set of useful folding patterns we use in our designs for a peristaltic worm robot is tabulated in Fig. 1, where mountain and valley folds are indicated by dashed and solid lines, respectively. The corresponding semifolded shapes are also included in this figure for better visualization.

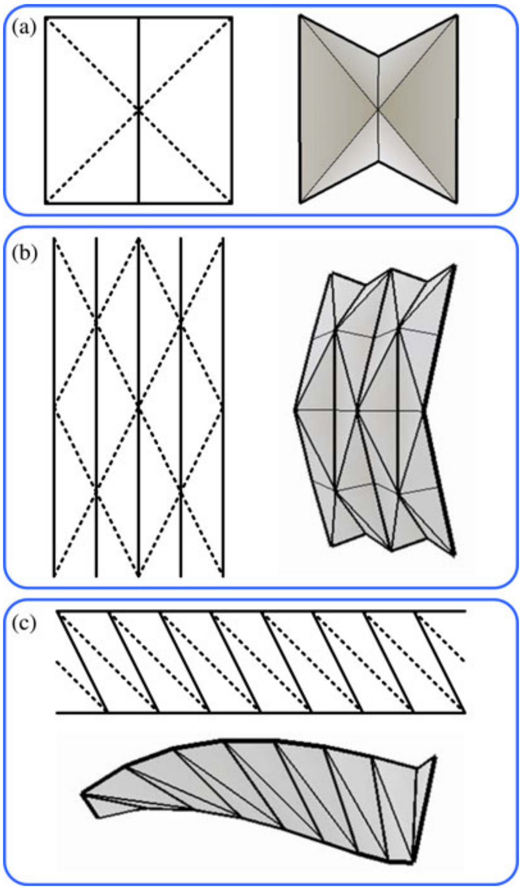

Fig. 1. Crease patterns of significant folding elements, suitable to generate key motions for robotic applications, with their respective semifolded shapes using the Rigid Origami Simulator in [14]. (a) Waterbomb base, (b) Yoshimura Pattern, and (c) Diagonal Pattern. In these sketches, dashed lines indicate mountain folds and solid lines indicate valley folds.

The first crease pattern displayed in Fig. 1 is the waterbomb base. This element lets a flat sheet to collapse on itself, generating an ideal axial contraction segment. Furthermore, this can be considered as a basic tile, which can be arranged in an alternating array and attached on both ends to yield a cylindrical tube, as shown in Fig. 2. The result is a tubular honeycomb structure, which exhibits a negative Poisson's ratio between the radial and axial dimensions, in addition to being an axial contraction unit. We can use the negative Poisson's ratio property to contract the tube axially by compressing it in the radial direction. This could yield to an artificial muscle to pull on a tendon, for instance. The same structure is previously used as an SMA stent that can be activated by the natural body heat in [15].

The Yoshimura pattern is named after a scientist who observed this structure in thin-walled cylinders buckled under axial compression [16]. It has a basic structure of a diamond folded along its diagonal. The last pattern is called the diagonal pattern, which is similar to the Yoshimura pattern, except the fundamental diamond is angled to form a parallelogram. This pattern is

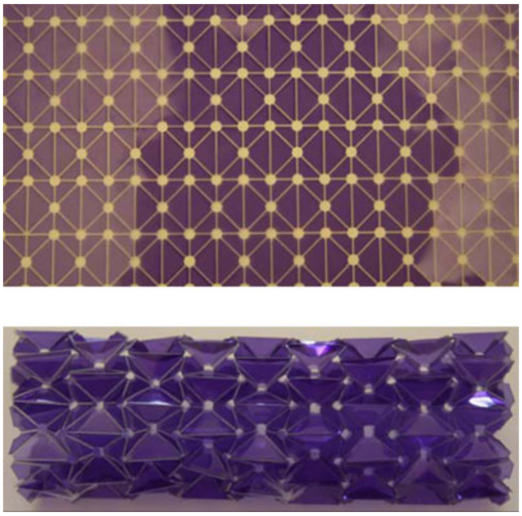

Fig. 2. Origami tube design with a negative Poisson's ratio between the radial and axial dimensions. The negative Poisson's ratio is achieved due to the alternating waterbomb base pattern (top). The tube (bottom) is fabricated by our laser perforation process on a flat polymer sheet and manually folded into shape.

also observed in thin-walled cylinders that buckle under axial compression and torsion [16]. These buckling patterns are especially useful in generating cylindrical axial or rotary motion units, as they follow the natural tendencies of the material for these motions.

The three origami patterns can be combined to provide arbitrary motion capabilities in the following way: the waterbomb base pattern can expand and contract in all directions, Yoshimura pattern generates a purely translational motion element, and the diagonal pattern yields rotary motion coupled with translational motion.

We can draw a parallel of this robotic design paradigm to established printed control board design techniques. Treating a set of crease patterns as components, and obeying rules of origami, we design functional 3-D structures and mechanisms that can generate a certain shape with certain motion capabilities. We currently design our robot bodies manually, but a software tool to automate this process is feasible, as the library of useful fold patterns grows in size. Currently, we have designs that incorporate many of the mentioned base fold units, some of which are displayed in Figs. 2 and 4. These figures show the crease pattern and the folded shapes of various designs for a segmented worm-like locomotion system.

A. Fabrication

There are many fabrication technique alternatives for flat substrates. Well-established high precision machine tools are appropriate for relatively thick sheets. For foldable thin materials, however, there are more suitable techniques. Advances in microfabrication techniques, for instance, can be utilized for this task. These methods routinely generate intricate 2.5-D features on a flat surface, which can be translated for our objectives to functional robotic structures. They include a range of subtractive or additive processes, such as photolithography, laser machining, and molding, which have the potential to form the necessary features that enable a film to be folded into useful 3-D structures.

With a suitable fabrication technique, we can form folding patterns on a thin flat substrate similar to creasing a sheet of paper, to create a tendency to fold along these patterns. We can achieve this tendency by reducing the bending stiffness of the material to a fraction of its original value at defined positions. As the bending stiffness of a material is heavily dependent on its thickness, reducing the material thickness is the most obvious way to program its stiffness along folding lines.

This study utilizes laser machining techniques as a representative fabrication method, and polymer films as the raw material, for simplicity and speed. Polymers machine well at longer wavelengths; therefore, we use a $\mathrm{CO_2}$ laser. With very low power and high speed laser settings, we can engrave polymer films rather than cut them, in order to etch the mentioned crease patterns. This way, we can reduce the thickness of the sheet to achieve flexural hinges on specified lines, which define the crease patterns.

Our initial prototypes used engraved crease patterns to some success. We found two limitations of laser engraving. First, the resulting creases have a stronger tendency to fold in one direction than the other as the remaining material is not symmetric around the neutral bending axis. Second, it was difficult to achieve repeatability as the crease line is weakened by laser machining and small variations have large effects. Thus, the material seemed to become more fragile, occasionally getting torn under repeated operation.

To remedy these issues, we employed another way to generate folding lines, to perforate the polymer sheet with a controllable density. Here, density is defined as the number of perforation holes per unit length. Laser cutting a series of small holes on a straight line has the same effect in reducing the bending stiffness at defined positions. The resulting perforations are symmetric and since only part of the fold line is affected by the laser, folds are robust to variations with no noticeable repeatability problems. Furthermore, adjusting the perforation density gives us a straightforward way to control the stiffness of the resulting fold.

Fig. 2 demonstrates a sample structure printed with the laser perforation process both before and after folding. This figure also displays our solution to a practical issue. At intersections where multiple folds coincide, high mechanical stresses can occur. We reduce these stresses by cutting out holes at these potentially problematic points.

B. Actuation

Driving the origami mechanisms requires compact and powerful actuators. There exist miniature DC motors, which can be used in combination with tendons, to actuate various parts of a foldable structure. For ease of integration and fabrication, however, we believe that it is more desirable to eliminate the motor and actuate the tendons directly. NiTi coils are appropriate for this task. NiTi coils are simple fibrillar actuators, making them straightforward to attach to holes on a flat sheet to easily

TABLE I
FABRICATION PARAMETERS OF VARIOUS MATERIALS

Material	Power	Speed	Thickness
Polyester	2 W	63.5 mm/sec	0.1016 mm
Polyether ether ketone (PEEK)	3.5 W	63.5 mm/sec	0.127 mm
Polytetrafluoroethylene (PTFE)	12.5 W	63.5 mm/sec	0.127 mm

distribute actuation over the body. NiTi is a shape memory alloy, which is well known for its high energy density (as high as 1200 J/kg [17]). It can be wound in a coiled spring structure from a straight wire around a core with a given diameter following the procedure shown in [17]. This spring actuator is essentially a micromuscle, which is especially useful in mesoscale applications.

NiTi actuation is based on a temperature-dependent solid-state phase transition in the alloy structure. Being a thermal process, it can be easily driven by Joule heating of the conductive material, despite having limited efficiency.

Another important limitation of NiTi coil springs is the potential repeatability problems among individual actuators. Since they are not generally fabricated in an automated fashion, the actuators may have variations in length or strength. This could be especially problematic for Joule heating, as different resistance values wired in parallel to a voltage supply would pass different currents, which in turn creates asymmetry in actuation. Hence, to reduce such problems, a series electrical connection is more suitable for multiple springs to undergo a similar contraction response. If possible, it is preferable to reduce the number of NiTi coil fibers acting on the same degree of freedom.

For the systems we experimented with, a single SMA spring for each desired motion with a large, safe driving current for shorter periods to improve on the efficiency works well. Pulsing larger currents creates a fast temperature increase in the alloy, before most of the heat can be dissipated, since the heat loss by free convection is reduced. This efficiency benefit has been previously investigated in depth in [18].

While NiTi springs have the benefit of being compact to pinpoint the exact part of the structure to create motion, their thermal operating principle creates a constraint on the choice of body material. We actuate the springs by Joule heating up to the transition temperature. This causes local high temperatures to occur on the body, especially at the points of attachment. To make sure that the material does not melt at this temperature, we use polymer sheets that have a comfortably higher melting temperature or thermoset polymers with sufficiently high glass transition or deflection temperatures. A list of materials investigated for this purpose is tabulated in Table I. Note that this table displays parameters tuned for our particular laser cutting system (Versa VLS 3.50) with a 50-W CO_2 laser at a wavelength of 630–680 nm. These materials were obtained from McMaster-Carr.

The ideal material should have excellent thermal properties and dimensional stability. First, we tested Polyimide sheets of various thicknesses, but found that Polyimide tends to char and becomes brittle around the small holes, when it is perforated with our process. After testing resulting folds with different perforation densities, we concluded that Polyimide folds break after tens of repeated folding/unfolding cycles. Three materials that tested well were polyester, polyether ether ketone (PEEK) and polytetrafluoroethylene (PTFE), all of which yielded well defined stable creases.

Among these, polyester was the easiest to pattern. It is the least expensive of the three. However, it has a low melting temperature, not suitable for repeated actuation with SMA coils. Hence, we use this material to test new designs without actuators. PTFE has good thermal properties, but we found that it is harder to cut and yields low stiffness folds. The best material for our purposes was PEEK, which is relatively easy to cut, has good thermal properties, and yields a useful amount of stiffness at the folds that are neither too strong to allow motion nor too weak to provide passive antagonism for NiTi coil actuation. We use this material for our final prototypes.

While our origami designs make use of active elements to generate motion, in the design step, we must also account for easy attachment of NiTi springs on the body to actuate each of these active elements. The fabricated sheets are manually folded into shape and the actuators are attached in such a way that they contract to create motion of the active elements, while keeping the structural elements stationary. Building our current designs takes less than an hour with this method.

III. BUILDING AN ORIGAMI ROBOT WITH PERISTALTIC LOCOMOTION

We have applied the process of building origami robots to the creation of a worm robot. The worm is a tubular structure that has a number of segments that can contract axially in order to undergo worm-like peristaltic locomotion.

Peristalsis is a simple locomotion process employed by worms. By changing their body shape, these small limbless invertebrates can modulate friction forces to pull themselves forward without the need for a complicated limb motion. Generating a traveling contraction wave over the body length, peristalsis results in linear motion. Especially for limited spaces, this crawling motion may enable robust locomotion.

To move their bodies, worms generate frictional anisotropy, so that frictional forces in the backward direction are greater than those in the forward direction. This enables the ground contact points to have a tendency to slide forward more easily than backwards, yielding a net forward motion. Earthworms, for instance, achieve this directional friction by hair-like setae. The setae can be considered as simple bristles or legs that anchor to the surface to prevent backward slippage [19], [20].

For our robot to crawl with peristaltic locomotion, we utilize a similar mechanism to achieve frictional anisotropy. This mechanism comprises two passive feet on both ends of the robot, as shown in Fig. 3. We place the feet by incorporating two rectangular flaps protruding from the body on the same crease pattern. As these flaps are semifolded parallel to each other at an approximately 45° angle, they approximate a saw-tooth structure. Each flap holds its position for backward motion by anchoring itself to small asperities on the ground, while sliding with little resistance for forward motion.

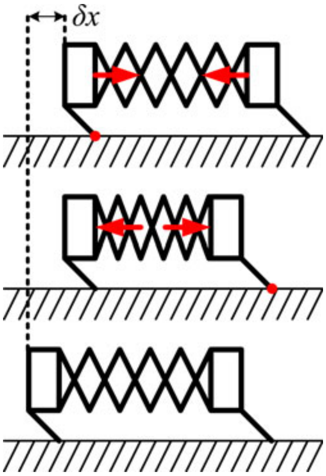

Fig. 3. Frictional anisotropy by folded passive flaps. During contraction, front flap resists backward slippage while back flap slides forward. During extension, front flap slides forward while back flap holds its position.

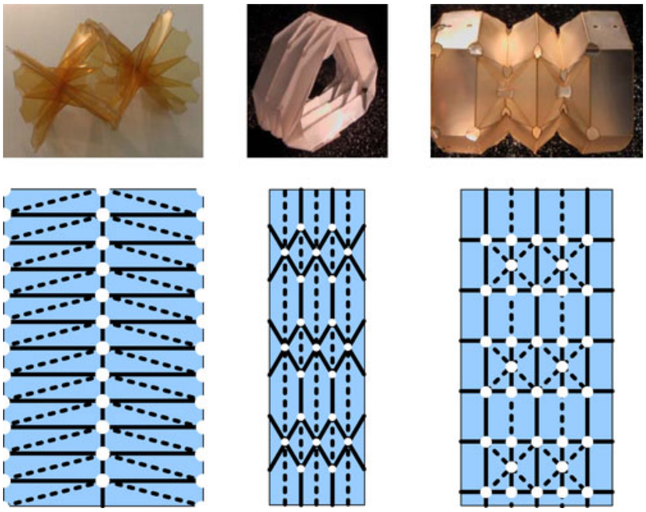

Fig. 4. Three contractile segment designs we investigated for an origami-inspired worm robot (top), with their respective crease patterns (bottom): the diagonal pattern (left), the Yoshimura pattern (middle), and the waterbomb base pattern (right).

A. Body: Axial Contraction Segments

In our initial study to create an origami-inspired robot, we built a tubular structure exhibiting negative Poisson's ratio between radial and axial directions. This structure is shown in Fig. 2. By radially winding an SMA coil around this structure, contractile segments are achieved. Due to the negative Poisson's ratio property of the structure in Fig. 2, actuating the SMA coil radially causes the segment to also contract in the axial direction. In our preliminary experiments, we have achieved this behavior with three issues. First, the tube does not have a large enough passive stiffness to return back to its original state after being actuated (e.g., to detwin the radial actuators). Second, attaching the SMA coil actuators on the outside to yield a uniform radial contraction is not trivial. Third, even though printing the body is fast, folding such a complicated structure is difficult.

For these reasons, based on our experience, we designed three types of contractile segments, utilizing different fold patterns, as shown in Fig. 4. These designs also demonstrate the power of folding patterns and the range of possibilities to generate desired properties. We compared these designs on three aspects, which were problematic on our initial design: 1) stiffness, 2) actuator attachment, and 3) ease of folding. The ideal design should meet all these metrics to have high stiffness, easy actuator attachment, and easy folding.

The first design in Fig. 4, on the left, is based on the diagonal pattern and previously used in "spring-into-action" origami design by Jeff Beynon [8]. This axial segment is composed of two stages of diagonal folds in opposite directions. Since diagonal folds create a rotary motion in addition to axial compression, to achieve a purely axial motion between the two ends, the reverse rotation of the second stage cancels the forward rotation of the first. This design generates a large deformation and has a high stiffness, but it is very difficult to fold and actuator attachment is not trivial.

The second design, in the middle, is a modified version of the Yoshimura pattern. It is easy to fold and since no rotary motion takes place, SMA coils can be attached on both ends of the segment on the outside and pull it to contract. Nevertheless, this pattern forms the tubular shape when completely folded, which means that its natural state is fully folded and does not have a high stiffness to counteract the SMA coil contraction.

The third design, on the right, is similar to the second one. It is composed of three waterbomb base folds that are placed in 120° increments over the circular cross section. We found that putting two of these active elements next to each other, we can create a large deformation and achieve a useful segment stiffness. Since this folding pattern does not naturally roll into the final cylindrical structure, it has a certain stiffness resisting the contraction. It is easy to fold and actuators can be attached on both ends of the segment as for the Yoshimura pattern. Due to its superior properties in all of our metrics, we use this design to build our printed worm robots.

Inspired by the earthworm, our robot has multiple contractile waterbomb base segments that are physically connected in series, in a cylindrical body. The body cylinder is created by attaching two ends of the flat sheet with tape. The crease pattern of this design, laser machined on a PEEK substrate, is shown in Fig. 5. This pattern is "printed" in 17 min.

The physical and electrical connection of the SMA springs needs to be taken into account in the design step. They need to be easily attached and activated. The holes we place on the body to reduce the maximum stresses provide us with a good way to attach SMA coils to the structure, especially since the actuators can be considered as strings. With the addition of smaller holes to hold the two ends in place for electrical connection, we are able to activate the NiTi springs by passing current through them.

To make sure contractions occur evenly, we use a single SMA spring woven through each segment. This way, the force pulling on the segment will have less variation along the perimeter of the cross section, reducing the amount of undesired bending. The weaving pattern of the actuators (over and under the sheet,

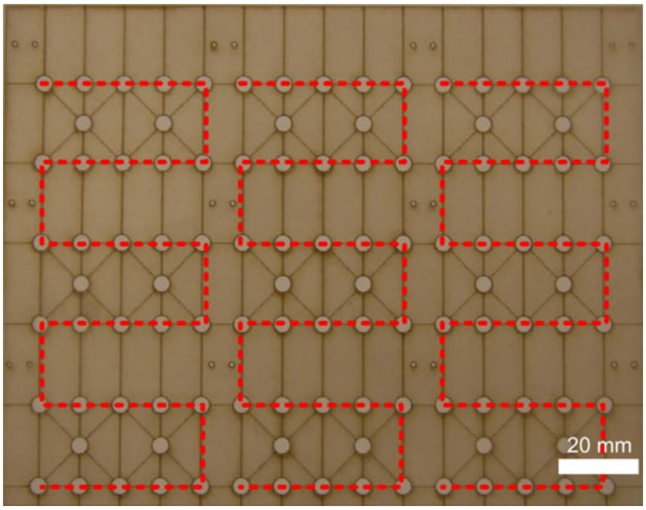

Fig. 5. Crease pattern of an origami-inspired mobile robotic body that can undergo earthworm-like locomotion.

highlighted in Fig. 5 with red-dashed lines) uses the existing stress relief holes on the body. The ends of the coils are placed through smaller actuator attachment holes and crimped in place by a metallic ring. When the top and bottom edges are attached, the two ends of the actuators meet, for ease of electrical connection. The actuators are made by tightly coiling a 250 μm NiTi wire around an 800 μm core using a custom coiling setup. These parameters yield a segment contraction of approximately 4 mm and require approximately 6 s to passively cool down.

The contraction elements are essentially passive springs before actuation. For peristaltic locomotion, the segments should contract and relax sequentially. NiTi coil actuators contract by active heating and relax by passive cooling and benefit from an external tension load for detwinning. Hence, the relaxation of the actuator tends to take more time. The passive stiffness of the segment helps with the relaxation as it pushes the actuator towards its relaxed state.

B. Brain: Control

To drive the peristalsis for locomotion, we need to individually address and activate each segment. This simple gait algorithm starts the contraction wave at the back of the robot and sequentially moves it over the length of the robot. For longer robots with many segments, multiple waves can be run simultaneously with a phase shift. For this case, we use a three-segmented robot with a single wave.

Even with the help of its tunable stiffness providing antagonism, the relaxation of a segment still takes more time than its contraction period. The timing requirements of relaxation pose a constraint on the number of segments. The peristalsis that will drive the robot is a wave of axial contraction. After a segment is actuated, it should have enough time to relax until the wave travels over the length of the body and reaches the segment again. The same thing can be achieved by placing cooling periods between subsequent contractions of neighboring segments, despite with a loss of speed. For simplicity, we used the latter technique with just three segments in this study.

TABLE II
CONTROL AND PERFORMANCE PARAMETERS FOR THE ORIGAMI WORM

Parameter	Value
Actuation Current (I_{on})	300 mA
Actuation Period (τ_{on})	4 sec
Cooling Period (τ_{off})	6 sec
Actuation Power (P_{on})	2.4 W
Average Power (P_{mean})	0.96 W
Energy over single cycle (E_{cycle})	28.8 J
Average robot speed (v_{mean})	18.5 mm/min
Robot mass (m)	4.2 g
Cost of Transport	0.74 J/g/mm

We used a custom PCB, equipped with an ATmega88PA microcontroller to control the robot. The PCB has eight digital outputs that can be used to drive eight MOSFETs, which are connected to a separate power line to protect the microcontroller from large currents. Using the digital outputs, we can regulate power to the individual NiTi coils to produce the desired gaits. We plan to use the five extra power drivers for steering. In addition, the board has eight 10 bit A/D channels for a closed-loop implementation.

The microcontroller runs the robot by timing actuation periods τ_{on} followed by cooling periods τ_{off} between each contraction of segments. The average resistance of the NiTi coils is about 26.5 Ω. Hence, for a safe driving current of about $I_{\text{on}} = 300$ mA and activating only one actuator at a time, about 8 V of voltage is used in the power line. The control and performance parameters of these experiments are summarized in Table II.

With this gait algorithm, assuming that no backward slippage occurs, the maximum theoretical velocity of the robot can be modeled as

$$v = \frac{n_{\text{wave}} n_{\text{seg}} \delta x}{n_{\text{seg}} \tau} = \frac{n_{\text{wave}} \delta x}{\tau} \tag{1}$$

where $\tau = \tau_{\text{on}} + \tau_{\text{off}}$, n_{seg} is the number of segments, n_{wave} is the number of waves running along the robot, and δx is the compression amount of each segment. Note that the number of segments is canceled out and does not have an explicit effect on the speed according to this equation. Nevertheless, its mentioned effect on the cooling period τ_{off} requirements indirectly changes the speed value.

C. Experimental Results

As the crease pattern is fabricated on a PEEK substrate and folded into 3-D shape, the actuators are attached on the body and the electrical connections are made by crimping thin copper wires. The whole process of building this robot takes less than an hour. The waterbomb base crease patterns are 20 mm and approximately 10 mm long before and after folding, respectively. Correspondingly, the total robot body length is about 100 mm after folding and before actuation. The robot body is 4.2 g in weight.

With the control algorithm described in Section III-B, the resulting crawling locomotion of the robot is shown with

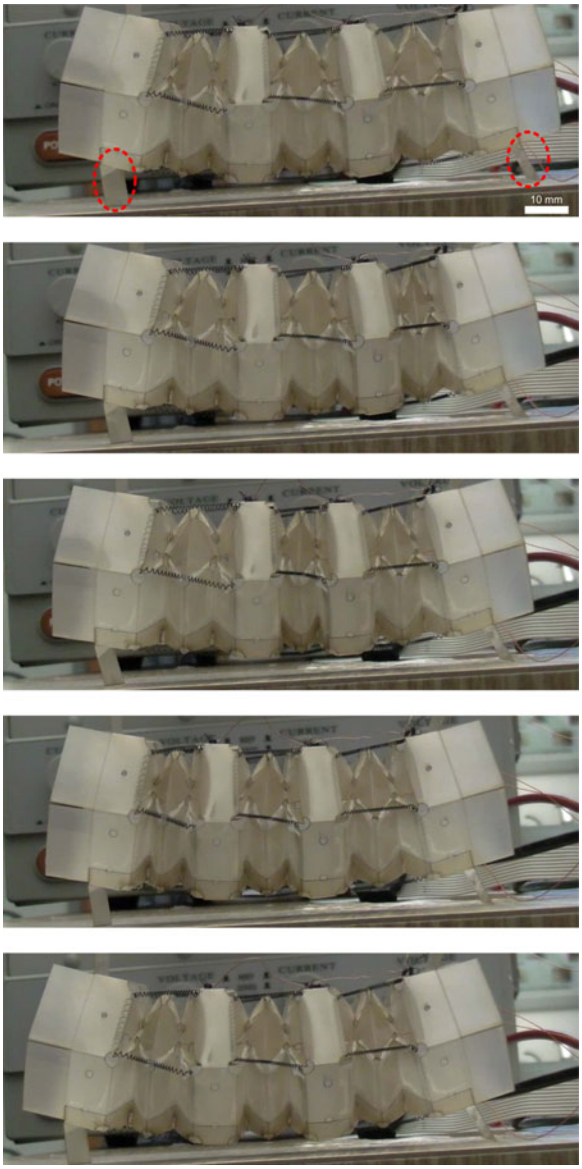

Fig. 6. Peristaltic crawling locomotion of the robot is displayed in a sequence of snapshots, from top to bottom. On the top, the initial relaxed state (with the legs marked) is displayed. The three following images show the contraction of each segment, which correspond to the control signal supplying current to their embedded SMA coils in order. The bottom image is the final relaxed state.

snapshots in Fig. 6. The two legs protruding under the robot on both ends can also be seen in this figure. As mentioned before, the legs are folded in the same direction, creating a frictional anisotropy to drive the robot forward. In future implementations, the legs themselves can be actively angled to drive the robot backwards. Note that, while a tetherless implementation using two miniature LiPoly batteries (3.7 V, 160 mAh, 2.3 g each) is feasible (yielding an operation time of 74 min with the parameters given in Table II), in these experiments, the robot is powered by off-board power.

We designed and printed a family of origami robots and mechanisms in different shapes and sizes, as displayed in Fig. 7. The robot shown in Fig. 6 is the latest one with feet incorporated. The feet are manually angled and tested for friction in forward and backward directions before experiments to make sure the necessary anisotropy is formed. The robot crawled on flat wood and paper surfaces on a tabletop, in a total of ten experiments, with about 100 mm displacements.

Fig. 7. Collection of origami robots and mechanisms fabricated by the proposed procedure. From left to right: the first column displays axial springs, second column shows the negative Poisson's ratio structures, and the rest are robotic worm bodies in various shapes and sizes. The horizontal robot is the final prototype used in experiments.

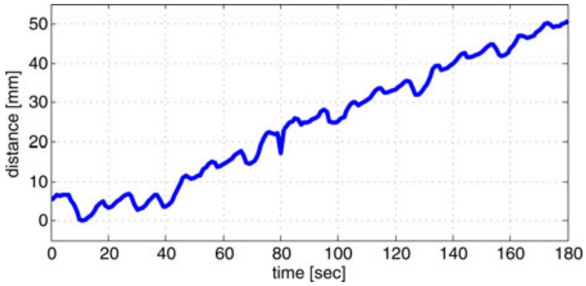

Fig. 8. Displacement of the origami worm robot over time.

To quantify the speed of the worm robot, we used image processing techniques. Using a webcam, an initial image of the background is taken first and the robot is placed. By driving the robot over the known background, its position can be accurately detected by simple background subtraction. We traced the forward edge of the robot with this motion detection setup and converted the pixel information to millimeters to achieve the displacement curve shown in Fig. 8.

The robot crawls about 50 mm in 3 min at an approximately linear rate for an average forward velocity of 18.5 mm/min, which is about 77% of the expected result from (1). The oscillations in the data coincide with the actuation of segments and show the effectiveness of the motion detection.

The speed of the robot can be improved with a loss of safety by increasing the input current and reducing the actuation period correspondingly. Another improvement can be made by using a longer robot with more segments to be able to reduce the cooling period between actuations. Using an actuation current $I_{\text{on}} = 1$ A and an actuation period of $\tau_{\text{on}} = 0.5$ s, leaving all other control parameters constant, the theoretical speed becomes 36.9 mm/min. Using these actuation parameters, we performed experiments on the repeatability of speed on three surfaces in Fig. 9.

In these experiments, the robot is placed on a flat surface and the time it takes to traverse a defined distance of 50 mm is

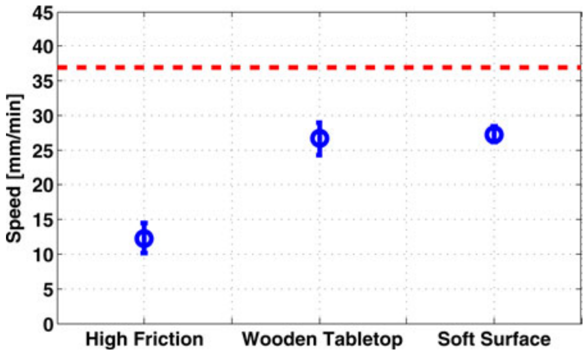

Fig. 9. Experimental investigation of the speed of the robot on three different surfaces. The (red) dashed line indicates the theoretical maximum speed for these experiments.

measured five times for each type of surface. We were expecting the best performance on a very rough high friction surface, since it would not allow the robot to slip back, but we found that the friction forces diminish motion in both directions, causing the feet to bend on the folds but not slide forward as expected. The average speed on this surface was 12.3 mm/min, about 33% of the theoretical speed.

We achieved similar results on a polished wooden tabletop and a foam soft surface, while the soft surface had a slightly larger average speed and smaller variation. The average speeds on these surfaces were 26.6 and 27.2 mm/min, or about 72% and 74% of the theoretical value, respectively.

IV. DISCUSSION

In this paper, we presented a robot fabrication method from flat sheets inspired by origami. Active 3-D structures and mechanisms can be easily created with speed and low cost. With this technique, many established 2-D fabrication methods can be employed in the creation of robots. We believe that this new approach of "printable robotics" will bring a new class of robots in the near future. For many applications, the robots can be kept unfolded when not in use, which will help with the storage and transportation problems that may arise.

In comparison to solid structures, a sheet folded into 3-D has lighter weight. The introduction of trusses in construction is analogous to the use of folded structures for robotics. When designed correctly, active folds of an origami robot become joints in the body to generate motion. On the other hand, passive folds (links) remain static. Since sheets have low flexural stiffness, the structure should be designed such that out-of-plane stresses on the static regions (links) are minimized. The origami worm shown in this study, for instance, is designed to have a high torsional strength over the body and axial forces create deformation in the active segments, but not on the passive regions. This robotic fabrication method is useful for relatively small-scale robots that do not carry large payloads and possibly in underwater or space robotics applications.

Some limitations of this paper also create future research opportunities. At this time, the fabricated crease patterns need to be folded manually into final shape. A better alternative is to create self-folding sheets [5]. This can be achieved using flat SMA actuators that can bend or fold, paired with small magnets to keep the stationary folds in place [5]. Once the body is transformed into its folded shape, a set of actuators that move the active significant folds can be driven to operate the robot.

Traditionally, the control electronics are separately created and electrical connections are manually made. Our planar robotic fabrication technique may allow an alternative. We plan to pattern conductive paths on the substrate and place electronic components on the body. This way, the robot body will also become its own control board, requiring only the power connection from a battery.

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