Towards Printable Robotics: Origami-Inspired Planar Fabrication of Three-Dimensional Mechanisms

Cagdas D. Onal, Robert J. Wood, and Daniela Rus

***Abstract*— This work presents a technique which allows the application of 2-D fabrication methods to build 3-D robotic systems. The ability to print robots introduces a fast and low-cost fabrication method to modern, real-world robotic applications. To this end, we employ laser-engraved origami patterns to build a new class of robotic systems for mobility and manipulation. Origami is suitable for printable robotics as it uses only a flat sheet as the base structure for building complicated functional shapes, which can be utilized as robot 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.**

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 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 robot parts with various functionalities [1]. Almost any 3-D structure imaginable can be designed in a software tool and fabricated in this fashion.

On the other hand, many 2-D 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 range of materials [2]. By a method of transformation between the fabricated sheets into 3-D structures that are useful in real-world robotic applications, printable 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 work was supported by Defense Advanced Research Projects Agency (DARPA) grant W911NF-08-C-0060 (Chemical Robots)

C. D. Onal and D. Rus are with the Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA {cagdas, rus}@csail.mit.edu

R. J. Wood is with the School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA rjwood@eecs.harvard.edu

To transform the patterned sheets into 3-D robots, many pieces can be individually fabricated and attached together to form the faces of the final robot. This, however, is a cumbersome process and 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, robotic functionalities can be embedded on the film 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 [2], [3], [4], [5], [6], [7], [8]. In this work, we identify specific folding patterns that generate useful functionalities and use these patterns 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 [9], [10]. 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 III discusses these actuators and their application.

II. ORIGAMI DESIGN

For our objective of building robots from flat sheets, folding is an appropriate tool to transform the fabricated planar structures to their final 3-D shape. It has the advantages of, designing and creating every part of the structure on a single sheet without the need for assembly, and placing elements that can be actuated, such as hinges, joints, or springs.

A foldable planar structure may be designed utilizing practices of the traditional Japanese art of origami, which is also becoming a technological tool in recent years. Currently, computational origami is a field of computer science with many practical applications [2], [4]. Researchers built computational tools that take a 3-D shape as an input and generate a corresponding crease pattern that yields the given shape when folded [11].

Similarly, in [12], Demaine *et al.* show that some origami crease patterns have a property of universality, which means that with a large enough sheet of paper, any 3-D structure can be sculpted. Another field of interest is active origami, which focuses on building structures, or mechanisms that can create motion [7].

Our first task was to identify folding elements that combine form with functionality. While a basic set of origami folds can be used to arrive at an arbitrarily complicated design, a special set of elements that can be placed at a portion of the design to incorporate a certain corresponding action set gives us a level of abstraction to simplify our designs. Some findings of our investigation are tabulated in Fig. 1, where mountain and valley folds are indicated by solid and dashed lines, respectively.

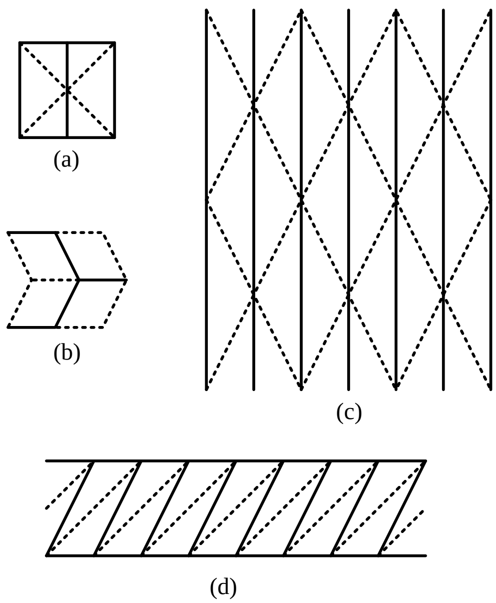

Fig. 1. Crease patterns of significant folding elements that were identified to be suitable for robotic applications; (a) Waterbomb base, (b) Miura Ori (Herringbone) tile, (c) Yoshimura Pattern, and (d) Diagonal Pattern.

The first element displayed in Fig. 1 is the waterbomb base. This folding pattern lets a flat sheet to collapse on itself, creating a useful axial contraction segment. When this basic tile is arranged in an alternating array structure, which is then attached on both ends, a cylindrical structure can be formed as shown in Fig. 2. The resulting tube has a honeycomb structure, which in addition to being an axial contraction segment, exhibits a negative Poisson's ratio between the radial and axial dimensions. This property makes it ideal to use as an artificial muscle that can be radially contracted to pull on a tendon, for instance. The same structure is used as an SMA stent graft that is activated by the body heat [13].

Similarly, the Miura Ori pattern that occurs when the tiles are arranged in a 2-D matrix exhibits a similar form of negative Poisson's ratio between the two planar degrees of freedom. It is popular in foldable maps and used in solar panel deployment [8] as the folded structure can be very compact compared to the final unfolded state.

The Yoshimura pattern is simply a diamond folded along its diagonal. It is named after a Japanese scientist, who observed this pattern in buckled thin-walled cylinders under axial compression [14]. The last pattern is also observed when thin-walled cylinders are axially compressed while under torsion [14]. Buckling patterns such as these are especially useful to create cylindrical axial or rotary motion elements as they follow the natural tendency of the material.

In summary, the waterbomb base and Miura Ori patterns can expand and contract in all directions, Yoshimura pattern generates a purely translational motion element, and the diagonal pattern yields rotary motion.

By treating a set of origami fold patterns as components and obeying rules of origami, we can design functional 3-D structures to create motion, very similar to designing a control board. We are currently designing our structures manually, but a software tool to automate this process is feasible. So far, we have designs that incorporate many of the mentioned significant elements, as some examples can be seen in Figs. 2 and 3.

III. ACTUATION

Compact and powerful actuators are necessary to drive the origami mechanisms that constitute the degrees of freedom in a robotic body. NiTi is a shape memory material, which is well known for its high energy density. 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 [15]. This spring actuator is essentially a micro-muscle fiber, which is especially useful in meso-scale applications.

NiTi actuation is due to a temperature dependant solid-state phase transition in the alloy structure. Being a thermal process, while it can be easily controlled by Joule heating, it tends to be rather inefficient.

Another important limitation of using NiTi springs is the possible repeatability problems between individual actuators. Since they are not generally fabricated in an automated fashion, the actuators may have variations in length or strength. This is 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 connection is more suitable for multiple springs to undergo a similar contraction response.

Due to these limitations, we employ a single SMA spring for each degree of freedom and prefer to use a large, safe driving current for shorter periods to improve on the efficiency. 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 [16].

While our origami designs make use of active elements to generate motion, in the fabrication step we must also account for easy attachment of NiTi springs on the body to actuate each of these active elements.

IV. FABRICATION

Many fabrication techniques are available to use on a flat substrate. For relatively thick sheets, for instance, high precision machine tools can be utilized. Nevertheless, for foldable thin materials other techniques are more appropriate.

This task can benefit from advances in microfabrication technologies. These fabrication methods generate intricately detailed structures on a flat surface. They include subtractive or additive processes such as photolithography or soft lithography providing many options to form the necessary features to achieve a film that can be folded to transform into useful 3-D structures.

An appropriate fabrication technique should allow us to form crease patterns on a flat sheet such that a tendency to fold at these patterns can be created. One way to achieve this tendency is to reduce the bending stiffness of the material to a fraction of its original value at certain positions. This can be achieved by reducing the thickness of the material at the folding lines by etching material. This creates a hinge at predefined locations, which define the crease patterns.

In this work, we are utilizing laser machining as a representative of applicable fabrication techniques, and polymer films as the raw material, for simplicity and speed. Using very low power laser settings, polymer films can be engraved rather than cut, to etch the mentioned crease patterns.

One limitation of laser engraving is that 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. To remove this problem, we employ another way to generate folding lines; to perforate the polymer sheet with a controllable density. Here we define the density as the number of perforation holes per unit length. Thus, we laser-cut a series of holes in a straight line to create the folding pattern. A perforation is symmetric and its density gives a straightforward variable to adjust the stiffness of the resulting fold. An example resulting structure of this process both before and after folding is shown in Fig. 2. In this figure, holes are also taken out at the points of high mechanical stress, which occur as multiple folds coincide. This is a notable practical issue in creating foldable structures in materials that are not necessarily suitable to be folded.

Fig. 3 displays two example axial spring mechanisms based on the Yoshimura and diagonal patterns. The spring in Fig. 3b was previously used in 'spring-into-action' origami design by Jeff Beynon [7].

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.

The final concern involves the placement of actuators. As mentioned before, the physical and electrical connection of the SMA springs need to be taken into account in the fabrication 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 also weave the SMA through 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.

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. This method of building a robot takes less than an hour for our current designs. In what follows, we will detail one mobile robot fabrication process as an example.

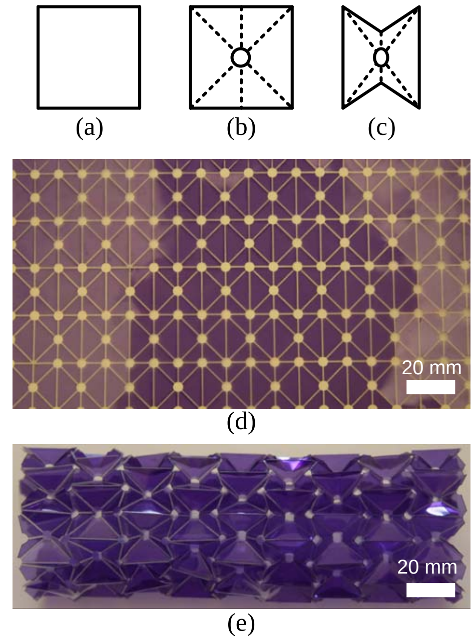

Fig. 2. Sketches of the fabrication process are shown in (a-c) for a single waterbomb base fold fabrication. A flat sheet in (a) is laser-cut in a series of small holes depicted as dashed lines in (b). The final structure is manually folded into shape in (c). An origami tube design with a negative Poisson's ratio between the radial and axial dimensions. The negative Poisson's ratio is achieved due to the alternating waterbomb base pattern in (d). The tube in (e) is fabricated by laser machining a flat polymer sheet.

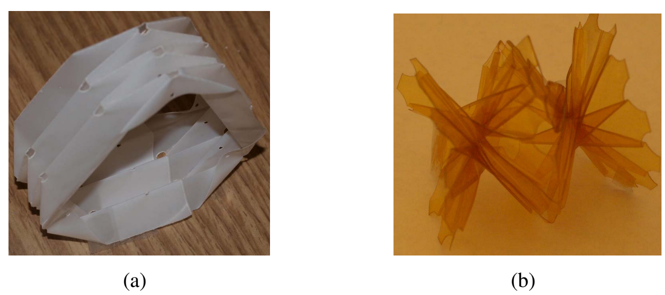

Fig. 3. Sample axial spring designs using (a) the Yoshimura pattern on PTFE and (b) the diagonal pattern on polyester. The torsion of one diagonal pattern is canceled by the inverse torsion of another to create a purely axial spring.

TABLE I

FABRICATION PARAMETERS OF VARIOUS MATERIALS.

Material	Power	Speed	Thickness
Polyester	2 W	2.5 in/sec	0.004 in
Polyether ether ketone (PEEK)	3.5 W	2.5 in/sec	0.005 in
Polytetrafluoroethylene (PTFE)	12.5 W	2.5 in/sec	0.005 in

V. ORIGAMI WORM ROBOT CASE STUDY

To demonstrate the proof-of-concept of printing 3-D robots on planar sheets, which are then transformed to their final shape by folding, we picked a simple system. This is a tubular structure that has a number of segments that can contract axially in order to undergo worm-like peristaltic locomotion.

A. Peristaltic Locomotion

Peristalsis is a simple locomotion process employed by worms. By changing their body shape, these small limbless invertabrates can modulate friction forces to pull themselves forward without the need for a complicated limb motion. Especially for limited spaces, this crawling motion may enable robustness in locomotion.

To move their bodies, worms generate frictional anisotropy, so that frictional forces in the backward direction dominate 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 attach to the surface to prevent backward slipping.

For a robotic structure that can crawl on a surface with peristaltic motion, a similar mechanism to achieve frictional anisotropy is useful. Accordingly, in our origami worm study, we place two passive legs on both ends of the robot. These legs are basically two flaps angled in the same direction so that they slip in one direction (forward) and stick in the opposite direction (backward).

B. Design

Inspired by the earthworm, our robot has multiple contractile segments that are physically connected in series, in a cylindrical body. The body cylinder is created by attaching two ends of the flat sheet. Each segment is composed of three waterbomb base folds that are placed in 120^o increments over the circular cross section. The crease pattern of this design printed by laser machining on a PEEK substrate is shown in Fig. 4. This pattern is 'printed' in 17 minutes.

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 relaxation. 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.

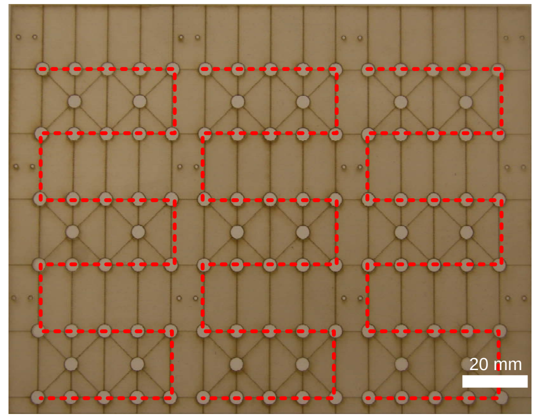

Fig. 4. The crease pattern of an origami-inspired mobile robotic body that can undergo earthworm-like locomotion.

Even with the help of its tunable stiffness providing antagonism, the relaxation of a segment still takes more time than its contraction period. The actuation times will be discussed in the next section, but the timing requirements of the 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 work.

To make sure contractions occur evenly, we use a single SMA spring weaved through each segment. This way, the force pulling on the segment will have less variation along the perimeter of the body, reducing the amount of unwanted bending. The weaving pattern of the actuators use the existing stress relief holes on the body for ease of assembly and is augmented in Fig. 4 with dashed red lines. The segments allow only the horizontal parts of the SMA coil to contract, creating an even axial compression of the segment. When the top and bottom edges are attached, the two ends of the actuators come close for ease of electrical connection.

C. 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.

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

TABLE II

CONTROL PARAMETERS FOR THE ORIGAMI WORM ROBOT.

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

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_{on} = 300 mA and activating only one actuator at a time, about 8 V of voltage is used in the power line. The parameters used in the 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:

$$v = \frac{n_{wave} n_{seg} \delta x}{n_{seg} \tau} = \frac{n_{wave} \delta x}{\tau}, \quad (1)$$

where $\tau = \tau_{on} + \tau_{off}$, 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 do 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.

D. 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. With the control algorithm described in Section V-C, the resulting crawling locomotion of the robot is shown with snapshots in Fig. 5. 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.

We designed and printed a family of origami robots and mechanisms in different shapes and sizes as displayed in Fig. 6. The robot shown in Fig. 5 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.

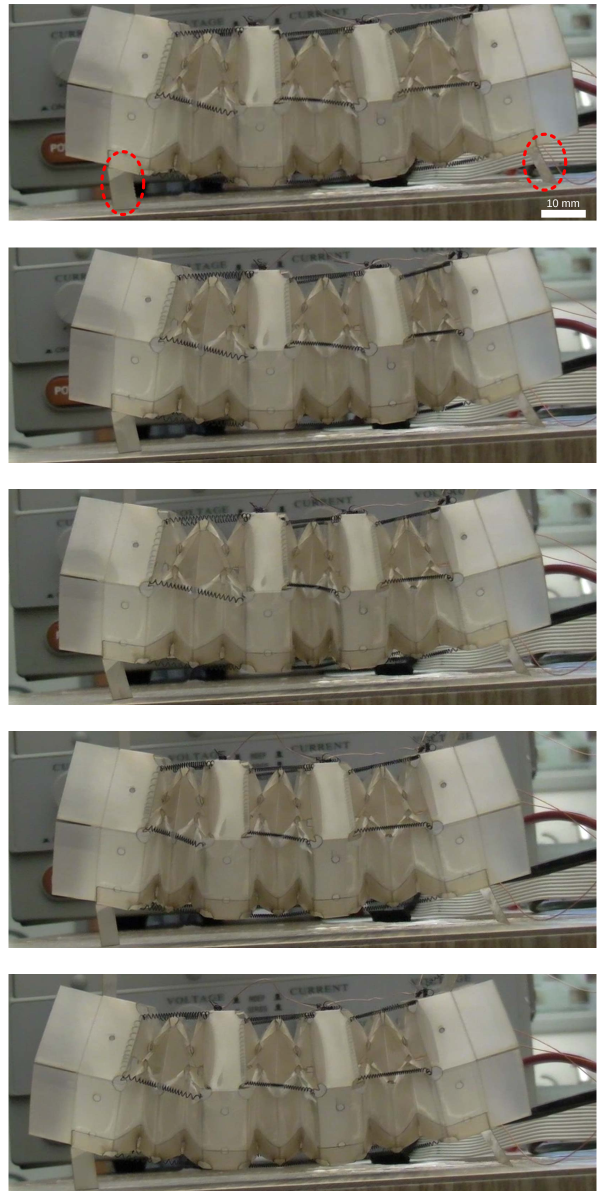

Fig. 5. The peristaltic crawling locomotion of the robot is displayed in a sequence of snapshots, from top to bottom. On the top, the initial relaxed state (with the legs marked) is displayed. The three following images show the contraction of each segment, which correspond to the control signal supplying current to their embedded SMA coils in order. The bottom image is the final relaxed state.

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. 7.

According to this data, the robot crawls about 50 mm in 3 min at an approximately linear rate. The oscillations in the

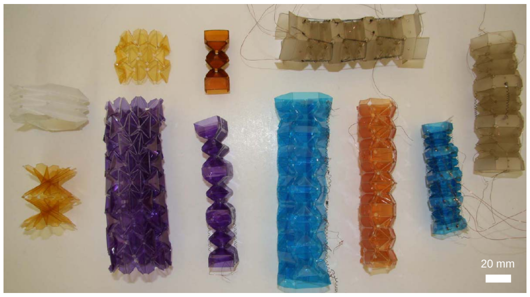

Fig. 6. A collection of origami robots fabricated by the proposed procedure. From left to right, the first column displays axial springs, second column shows the negative Poisson's ratio structures, and the rest are robotic worm bodies in various shapes and sizes. The horizontal robot is built for the origami worm case study.

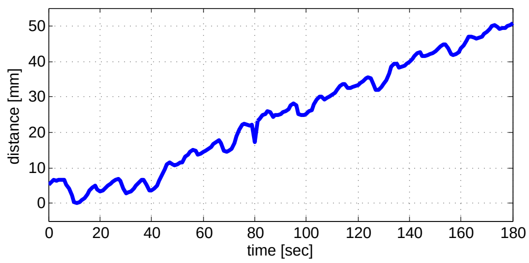

Fig. 7. The displacement information of the origami worm robot over time.

data coincide with the actuation of segments, and show the effectiveness of the motion detection.

VI. Discussion

In this work, 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 unfolded and kept as sheets 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. We believe that the introduction of trusses in construction is similar to this work 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 work, 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 the current work 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 [4]. This can be achieved using flat SMA actuators that can bend or fold, paired with small magnets to keep the stationary folds in place [4]. 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.

References

[1] H. Lipson and J.B. Pollack, Automatic Design and Manufacture of Artificial Lifeforms, *Nature*, vol. 406, 2000, pp. 974–978.

[2] N. Bassik, G.M. Stern, and D.H. Gracias, Microassembly based on hands free origami with bidirectional curvature, *Applied Physics Letters*, vol. 95, 091901, 2009.

[3] N. Benbernou, E.D. Demaine, M.L. Demaine, and A. Ovadya, A Universal Crease Pattern for Folding Orthogonal Shapes, *CoRR*, vol. abs/0909.5388, 2009.

[4] E. Hawkes, B. An, N.M. Benbernou, H. Tanaka, S. Kim, E.D. Demaine, D. Rus, and R.J. Wood, Programmable Matter by Folding, *PNAS*, vol. 107-28, 2010, pp. 12441–12445.

[5] J. Mitani, A Design Method for 3D Origami Based on Rotational Sweep, *Computer-Aided Design and Applications*, vol. 6-1, 2009, pp. 69–79.

[6] H. Okuzaki, T. Saido, H. Suzuki, Y. Hara, and H. Yan, A Biomorphic Origami Actuator Fabricated by Folding a Conducting Paper, *J. Phys.: Conf. Ser.*, vol. 127, 012001, 2008.

[7] C.C. Min and H. Suzuki, "Geometrical Properties of Paper Spring", *in the 41st CIRP Conference on Manufacturing Systems*, 2008, pp. 159–162.

[8] K. Miura, "Method of packaging and deployment of large membranes in space", *in Proc. 31st Congr. Int. Astronautics Federation*, 1980, pp. 1–10.

[9] S.-O. Seok, C.D. Onal, R.J. Wood, D. Rus, and S. Kim, "Peristaltic locomotion with antagonistic actuators in soft robotics", *in Proc. IEEE Int. Conf. on Robotics and Automation*, Anchorage, AK, 2009, pp. 1228–1233.

[10] Y. Matsumoto, H. Nakanishi, and S. Hirai, "Rolling Locomotion of a Deformable Soft Robot with Built-in Power Source", *in Proc. 11th Int. Conf. on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, 2008, pp. 365–372.

[11] T. Tachi, "3D Origami Design based on Tucking Molecule", *in Proc. 4th Int. Conf. on Origami in Science, Mathematics, and Education*, 2006.

[12] E.D. Demaine, M.L. Demaine, and J.S.B. Mitchell, Folding flat silhouettes and wrapping polyhedral packages: New results in computational origami, *Computational Geometry : Theory and Applications*, vol. 16(1), 2000, pp. 3-21.

[13] K. Kuribayashi, K. Tsuchiya, Z. You, D. Tomus, M. Umemoto, T. Ito, and M. Sasaki, Self-deployable origami stent grafts as a biomedical application of Ni-rich TiNi shape memory alloy foil, *Materials Science and Engineering A*, vol. 419, 2006, pp. 131–137.

[14] G.W. Hunt and I. Ario, Twist buckling and the foldable cylinder: an exercise in origami, *International Journal of Non-Linear Mechanics*, vol. 40, 2005, pp. 833-843.

[15] S. Kim, E. Hawkes, K.J. Cho, M. Jolda, J. Foley, and R.J. Wood, "Micro artificial muscle fiber using niti spring for soft robotics", *in Proc. IEEE Int. Conf. on Intelligent Robots and Systems*, 2009.

[16] C. Zanotti, P. Giuliani, A. Tuissi, S. Arnaboldi, and R. Casati, "Response of NiTi SMA wire electrically heated", *in Proc. 8th Int. Symp. on Martensic Transformations*, 06037, 2009.