Origami-Inspired Printed Robots

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***Abstract*—Robot manufacturing is currently highly specialized, time consuming, and expensive, limiting accessibility and customization. Existing rapid prototyping techniques (e.g., 3-D printing) can achieve complex geometries and are becoming increasingly accessible; however, they are limited to one or two materials and cannot seamlessly integrate active components. We propose an alternative approach called *printable robots* that takes advantage of available planar fabrication methods to create integrated electromechanical laminates that are subsequently folded into functional 3-D machines employing origami-inspired techniques. We designed, fabricated, and tested prototype origami robots to address the canonical robotics challenges of mobility and manipulation, and subsequently combined these designs to generate a new, multifunctional machine. The speed of the design and manufacturing process as well as the ease of composing designs create a new paradigm in robotic development, which has the promise to democratize access to customized robots for industrial, home, and educational use.**

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

I. Introduction

THE high costs and the lack of customizability of traditional robotic systems are two major impediments to their widespread use as tools, consumer products, and educational artifacts. These limitations are driven by the fact that traditional robotic systems require highly specialized fabrication and assembly processes. This results in long and expensive development and manufacturing processes, costly reconfiguration of assembly lines, and lack of agility in bringing new ideas to production.

While 3-D printing offers a potential route to the rapid fabrication of customized robot components [1], this technology faces significant challenges to become accessible to the average user. Current fine-resolution, multimaterial 3-D printers are expensive and challenging to operate. More fundamentally, current approaches to 3-D printing, or solid freeform fabrication, are each limited to a single category of build materials (e.g., extrudable polymers, UV curable polymers, or powdered materials that can be selectively sintered) and have difficulties printing structures with high specific strength (e.g., rigid shells) because they require horizontal surface area for interlayer adhesion [2]. Much current research attempts to address these challenges by developing exotic print materials for new structures such as biological tissues [3] and microelectrodes [4], or by developing inexpensive, open-source 3-D printers that can be "hacked" for new applications [5], [6]. However, the integration of active materials and structures such as actuators, sensors, and electrical circuits for computation is still out of the reach of 3-D printing techniques for the foreseeable future. Without significant breakthroughs in materials, integration, and printing technologies, 3-D printing of fully functional, monolithic, lightweight, inexpensive robots will not be possible. Likewise, educational and hobbyist robot kits do not offer sufficient customizability or adequate performance for many applications.

We previously presented an alternative approach to rapid, customizable fabrication of 3-D structures through the origami-inspired folding of 2-D robotic sheets [7]. In this previous work, we presented a universal robotic origami sheet capable of forming multiple shapes using a universal origami folding algorithm. Given a large enough sheet, this approach can theoretically be used to fold any polyhedral surface made up of unit cubes on the cubic lattice. However, practical concerns limit the usefulness of universal folding sheets in many applications. In particular, in the fabrication of robotic systems, folding actuators and sections with multiple folded layers add unnecessary mass and cost to the systems. Additionally, the box-pleat pattern approach limits the resolution of the assembled structures.

Here, we present an approach to develop 3-D electromechanical machines that assembles structures and mechanisms by folding. Instead of using universal sheets that can fold into any shape, we take the antithetical approach and develop a customizable design process for each desired object [8]. With a manufacturing process that is universal at design time, we create smart laminates that fold into corresponding structures or mechanisms. Unlike other additive manufacturing methods, these laminates contain an electronics layer for control and actuation of the folded mechanism. Starting with a parameterized template, we instantiate devices with performance characteristics (speed, payload, etc.) optimized for a particular application. To demonstrate this print-and-fold process, we created prototypes that address

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This paper has supplementary downloadable material available at http://ieeexplore.ieee.org provided by the authors. This material comprises two figures and five videos. Supplemental figures display two instantiations of the same printable template (Fig. S1) and the servo-actuated hexapod climbing stairs (Fig. S2). Supplemental videos display two printable hexapods playing chess (Video S1), printable robot manufacturing steps (Video S2), performance characterization of the printable mobile manipulator (Video S3), pick-and-place demonstration of the printable gripper (Video S4), and performance characterization of the SMA and servo-actuated printable hexapods (Video S5). The total size of this material is 53.6 MB.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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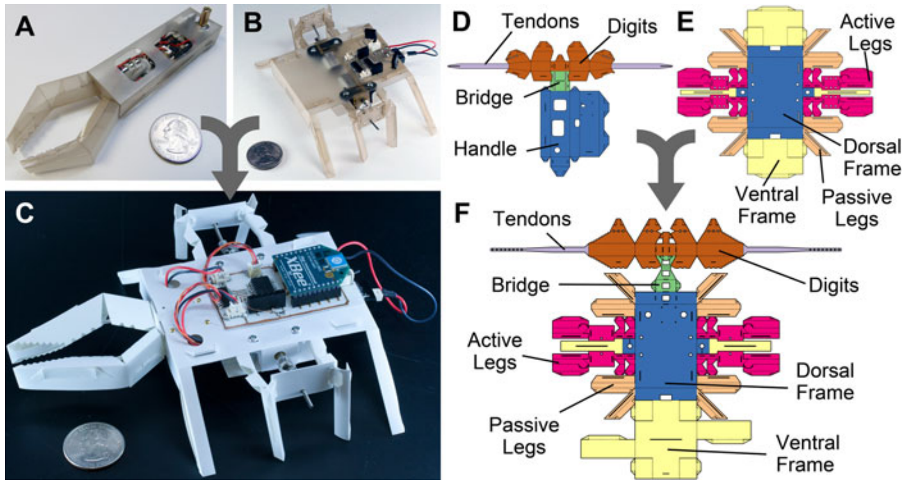

Fig. 1. Composition of origami-inspired printable robot designs. Despite the highly integrated nature of printable robots, existing functional designs can be composed to generate new, more capable robots. To demonstrate this, we developed a (a) robotic manipulator and a (b) legged robot, and combined these two designs to create (c) a mobile robot capable of manipulation (see Video S1). Each robot was fabricated in less than 3 h for less than $50 using the proposed origami-inspired printed fabrication approach. Each photograph contains a US quarter for scale. (d) Corresponding 2-D fold patterns are shown for the manipulator, (e) legged robot, and (f) mobile manipulator with subcomponents colored and labeled. Solid lines represent cuts and dotted lines define crease locations.

the canonical robotics challenges of manipulation and locomotion. The prototypes described in this paper are a legged robot and a gripper [see Fig. 1(a) and (b)].

We demonstrate that printable prototypes can be designed and fabricated rapidly, inexpensively, and that the resulting devices are lightweight and functional. Additionally, we demonstrate the ability to build upon existing templates to create new, increasingly complex designs using composition. We were able to mathematically compose the designs of a legged robot and a robotic gripper into an ant-inspired design capable of both locomotion and manipulation [see Fig. 1(c)]. The same print-and-fold process used to create the legged insect prototype was used to create the gripper and the composed device.

II. Origami Engineering

The core technique that enables printable robot manufacturing is folding. Folding, as opposed to traditional machining or additive manufacturing processes, is an efficient approach to the fabrication of 3-D structures found frequently in nature but rarely utilized in engineered systems. Our planar design and manufacturing approach produces printed 2-D precursors that are subsequently folded into ultralightweight, rapidly and easily manufacturable, and fully functional 3-D robots. Folded systems can be stored and transported compactly. Examples of hollow structural members can be found throughout nature from insect exoskeletons to mammal bones. In machine fabrication, the result of a print-and-fold process is less waste, better size scaling, and structures with high specific strength. Folding hollow structural elements reduces effective density while utilizing inplane strength of flat sheets. The hollow geometry of these members is similar to materials with the highest specific strength values measured [9].

Folding has previously been used in the fabrication of legged robots [10]; however, taking inspiration from origami, we follow a much more monolithic approach. Our devices are folded from a single laminate without any additional fastening or adhesives. The body material also serves as a circuit board for an integrated distributed electronics layer. Rigid members are achieved by folding hollow shells as opposed to adding extra layers or stiffening material. This monolithic approach allows for a standardized design and fabrication process with design composability, reduced assembly operations during fabrication, and encoding of assembly steps on the device itself. Additionally, it enables self-deployable systems [11], [12].

For insights into folding complex structures and mechanisms from flat sheets, we turn to the traditional Japanese art of origami. Origami-like folding has been observed in nature as a successful approach to self-assembly, from the molecules that make up life [13], to insect wings and plants [14]. Previous work has found origami-inspired folding to be useful in a variety of engineering applications such as mechanical component design [8], [15], metamaterial design [16], actuation [17], medical devices [18], programmable matter [7], folding of printed structures [19], and the compact storage of structures for space deployment [20]. Recent work has found origami folding to be particularly useful for fabrication and assembly at the micro- and nanoscales, where 3-D fabrication and direct manipulation are not practical. Demonstrated folded micro/nanostructures include various DNA shapes [21] and devices [22], molecular devices [23], supramolecular structures [24], micromirrors [25], electrochemical capacitors [26], structures with bidirectional curvature [27], folded graphene sheets[28], algorithmically designed self-folding polyhedra [29], and pop-up book inspired folded microdevices [30].

Theoretical results guide the design of folded structures by proving that it is physically possible to fold all single-vertex origami shapes [31], and that any polyhedral surface can be folded from a single sheet [32], [33]. These theoretical results provide an important basis for the use of folding as a general approach to the fabrication of robotic systems.

Previous work has demonstrated many structures and components based on origami-inspired folding using complex materials and processes; however, a complete electromechanical system using accessible, rapid, and straightforward fabrication processes has not been previously demonstrated.

III. Printable Robots

A. Origami-Inspired Design

Our printable fabrication process (described in detail in Section III-C) enables the rapid and inexpensive manufacturing of functional robots. There are two primary design challenges associated with this approach: Identifying foldable 3-D mechanisms to achieve a desired task, and specifying the associated 2-D fold patterns. Since folded robots, like most biological machines, are constrained to use noncontinuous rotational joints (i.e., flexures), we looked to nature for inspiration in our mechanical designs. The gripper prototype uses a bioinspired morphology with segmented digits actuated by internal tension elements (tendons) connected to a central microlinear servo actuator [see Fig. 1(a) and (d)]. Similarly, inspired by legged animals, we used ambulating designs for locomotion [see Fig. 1(b) and (e)].

The first step in designing origami-inspired robots is to define folds in planar form on a thin sheet of material, which either become fixed or flexural joints in the folded device. To define the folds, we considered etching part of the way through the thickness of the material to reduce bending stiffness at the desired fold lines. Since bending stiffness is a cubic function of thickness (see *Modeling* below), this method creates well-defined folds. However, these folds are not symmetric around the neutral axis of the sheet (a challenge for bidirectional folding) and, practically, we found etching a precise fraction of the thickness to be challenging. Instead of partial etching, we defined symmetric folds with lines of perforations. This approach produced direct control on the fold stiffness, which is linearly proportional to the fraction of unperforated material, and allowed greater repeatability and uniformity in printed robot fabrication.

A robotic mechanism typically requires rigid links and low impedance joints. In an origami robot, fold lines define joints but unsupported surfaces are too weak to act as links. To improve the stiffness of links and localize deformations at the defined hinges, we created fully constrained triangular beams by folding (see Fig. 5). Thus, the printable robot design process starts with a skeleton mechanism fulfilling functional requirements, which is supported with additional triangulation folds for structural rigidity at the links. The result is the generation of designs with ultralight, rigid mechanical members (digits, legs, etc.) connected by rotational flexures, similar to a spider's exoskeleton [34].

The hollow rigid beams of our designs were fixed together with tab-and-slot fasteners integrated into the mechanical design (see Fig. 2). This approach obviated the need for fasteners or adhesives during assembly, simplifying fabrication and leaving open the possibility of self-folding designs [11], [12].

We drew inspiration from origami techniques in developing principles for designing 2-D fold patterns. First, the surfaces of a desired structure's rigid members were unfolded (sometimes with the help of computer-aided design software or paper models) and connected with revolute joints (hinges). Final design templates were formed by the composition of discrete components as demonstrated in Fig. 1 into a single contiguous sheet in the unfolded state. This simplified fabrication and eliminated postfolding assembly steps. Where interference occurred between unfolded structures, we rearranged the components. For example, we combined two separate ventral frame portions of the legged robot [see Fig. 1(e)] into a single piece in the ant-inspired design to make room for a gripper attachment point [see Fig. 1(f)]. This is possible since, in general, 2-D crease patterns of a 3-D shape are not unique. However, this type of rearrangement requires creativity and may increase the complexity of the design. In cases where rearrangement would have overcomplicated the design, we opted for another alternative: *Bridge folds*. Bridge folds are extra, nonfunctional folds that connect two edges that should be adjacent in the folded state. The bridge folds in the ant-inspired design are indicated in Fig. 1. While useful, bridge folds introduce extra degrees of freedom in the mechanical design that must be constrained with additional tab-and-slot fixtures.

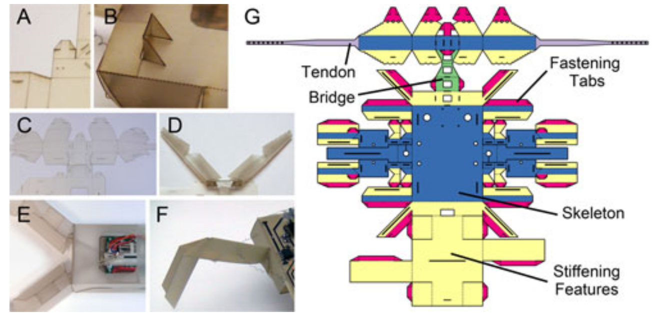

Fig. 2. Design principles that enable folding a robotic body from a single sheet. (a) and (b) Tab and slot features act as embedded mechanical fasteners. (c) and (d) Folded triangular beams create structural rigidity, and bridge folds bring together components of the 3-D machine that must be separated in two dimensions to avoid overlap. (e) Integration of microlinear servo and (f) shape memory alloy actuators in the folded body. (g) Schematic of single-sheet cut pattern for the mobile manipulator robot with folding features colored.

B. Modeling

Our printed robots are instantiations of design templates with free parameters that can be tuned to particular applications (see Fig. S1). These templates are based on mechanical models of the underlying mechanisms. As described above, the fundamental elements of our designs are rigid members formed by fully constrained hollow triangular beams and flexural hinges. Here, we describe our models for these elements.

One of the challenges of fabricating structures by folding is the inherent flexibility of thin sheets. The simplest fully constrained rigid member that can be formed by folding is a hollow equilateral triangular beam (see Fig. 3). The bending stiffness k_b of such a cantilever beam with width w_b, length L, material thickness t, and material elastic modulus E is given by

$$k_b = \frac{3Ew_b^3 t}{4L^3}. \quad (1)$$

Folding a triangular beam increases the bending stiffness of a strip of material by more than three orders of magnitude. As an example, the modeled bending stiffness of our printed mobile manipulator's static legs of length 38 mm and width 5 mm folded

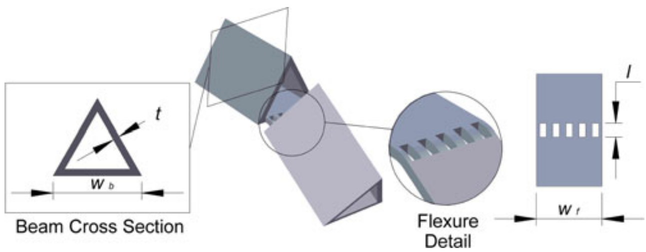

Fig. 3. Modeling printable robots. The two fundamental features of origami-inspired printable robots are hollow triangular beams and perforated flexures. The primary dimensions of these components are labeled in these schematics.

from 0.127-mm-thick polyetheretherketone (PEEK) is 781 N/m. For comparison, a steel rod of the same mass and length has a radius of 0.31 mm and a bending stiffness of 82 N/m is used.

The second key element of our robot designs is flexure hinges [35] (also known as *living hinges*). Small-length flexural pivots can be modeled as pin joints [36]. Defining f as the fraction of the hinge lines uncut by perforations, a flexure of length l, width w_f, and thickness t has a bending stiffness given by

$$k_h = \frac{E f w_f t^3}{12 l}. \tag{2}$$

The ratio of the stiffnesses of the rigid hollow triangular beam and the thin flexure is given by

$$R = \frac{EI_t}{EI_f} = \frac{3w^2}{ft^2}. \tag{3}$$

Thus, if the above beam is attached to a typical 5-mm-wide hinge with 50% perforation density constructed of 0.127-mm-thick material, the triangular beam is four orders of magnitude stiffer than the flexure. This allows us to neglect the stiffness of the hinges and treat them as pin joints.

Based on these fundamental models, we build up model templates for robot designs (e.g., hexapod robots). We are then able to tune model parameters (e.g., leg dimensions, actuation type) to tailor the robot design to meet the requirements of the target application.

C. Print-and-Fold Fabrication

To describe our fabrication process for printable robots, we must first define what it means for a robot to be printable. Without focusing on the particular technology (e.g., laserjet printing), we consider the experience from the point of view of the end user. Printing a robot—like printing a paper document—should be fast, inexpensive, and require minimal technical knowledge. Thus, in developing a process for fabricating printable robots, we limited ourselves to the use of tools that are readily available as commercial products, are inexpensive to purchase and maintain, and require minimal technical expertise in design and operation. Aside from ink printers, tools and processes that fit this definition include screen printing, photolithography, basic chemical etching, CO_2 laser cutting, pick-and-place assembly, and roll-on adhesives.

The printable fabrication process used to fabricate the devices presented here can be broken down into three steps: 1) defining the mechanical design and crease pattern; 2) printing the electronics onto the mechanical structure; and 3) assembly of the 3-D robot by folding (see Fig. 5, Video S2).

For the first step, we used a CO_2 laser machining system (VLS 2.3, Universal Laser Systems) to define the folding pattern in the mechanical layer, for which we used either 0.127-mm-thick PEEK or 0.127-mm-thick polyethyleneterephthalate. We chose these materials for their mechanical strengths, thermal and chemical resistance (for circuit fabrication), and availability in sheets. Crease lines were defined by perforating the material (see Fig. 5). By adjusting the perforation density, we were able to adjust the stiffness of the folds.

To fabricate the control electronics, we printed a circuit mask onto adhesive-backed copper tape using a solid-ink printer, and laminated this electrical layer onto the defined mechanical layer [see Fig. 5(a)]. A heated ferric chloride wet etch in a bubble etch tank removed the unmasked copper. We populated the electrical circuits with discrete components using pick-and-place assembly [see Fig. 5(b)]. With the electrical and mechanical systems fabricated, the final step was to fold the 2-D laminates along the predefined crease lines to create fully functional 3-D robots [see Fig. 5(d)].

Note that no 3-D printing is required for the creation of our origami-inspired robots. Besides the mechanical body and electrical circuits fabricated through planar processes, discrete off-the-shelf actuators are assembled to operate the robotic bodies. For instance, the prototype in Fig. 1(c) utilizes two miniature DC-motors that turn two laser-machined cranks to drive the active legs on both sides of the rectangular body, and a linear servomechanism to open and close the pincers.

D. Rapid Prototyping of Robots

The ability of the printable robots approach to rapidly generate inexpensive, functional systems allowed us to quickly iterate legged robot designs (see Fig. 4). Over the course of a year, we developed five prototypes, each of which was fabricated from detailed designs in less than 4 h, for less than $50 in parts, using commonly available fabrication tools. These designs explored the use of a variety of actuators (shape memory alloy or SMA coils, microlinear servos, and miniature geared DC motors) structure and mechanism designs, as well as controllers. The final, ant-inspired design performed remote-controlled locomotion at speeds of up to 410 mm/s (five body lengths per second, see Fig. 6), grasped and repositioned a variety of objects (see Video S1), and ran continuously for 38 min on one battery charge. While the integrated electronics in these robots are rectangular in shape, placed on the back of the robotic bodies, this is not a limitation of the printable robotics process. We have recently demonstrated distributed, customizable circuitry on the entire sheet as heating elements, which also enabled automation of the folding process [12].

The first three hexapod crawler robots shown in Fig. 4 share the same fundamental functional template, which consists of four legs that swing in the horizontal plane and a center pair of

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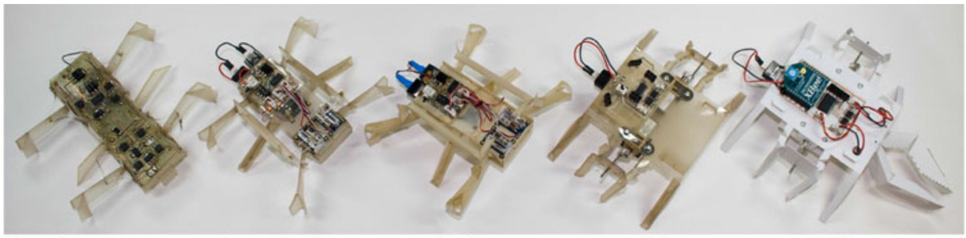

Actuation:	shape memory alloy	micro linear servo	micro linear servo	geared DC motor	geared DC motor
Folds:	124	120	312	142	176
Fabrication:	213 min	190 min	220 min	111 min	137 min
Body Length:	100 mm	73 mm	73 mm	75 mm	82 mm
Speed:	0.01 bl/s	0.09 bl/s	0.16 bl/s	3.05 bl/s	5.00 bl/s

Fig. 4. Evolution of folded legged robot designs. Manufacturing robots by folding printed structures enables rapid fabrication of inexpensive prototypes. The prototypes shown here achieve legged locomotion using a variety of body designs, actuators, and controllers. The labels specify the date of development, method of actuation, number of folds, fabrication time, and maximum speed measured for each design.

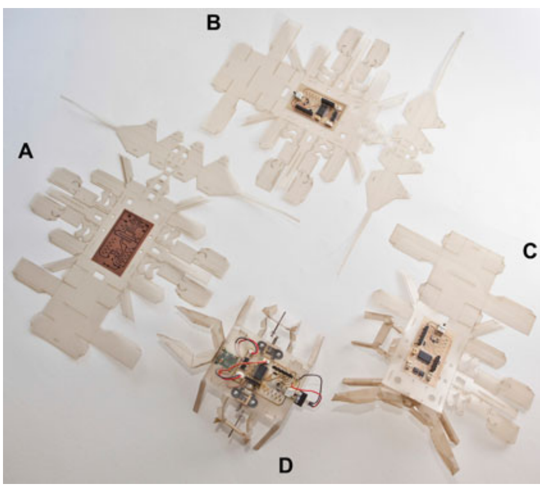

Fig. 5. Overview of the origami-inspired printed robot fabrication process. (a) Mechanical substrate (PEEK) is laser machined to define the crease pattern and the electrical system consisting of a circuit etch mask printed using a commercial solid-ink printer onto a layer of copper is laminated onto the mechanical substrate. (b) Exposed copper is etched away with ferric chloride, and discrete electrical components and actuators are added with pick-and-place assembly. (c) and (d) Design is folded and locked into place with integrated tab-and-slot fasteners.

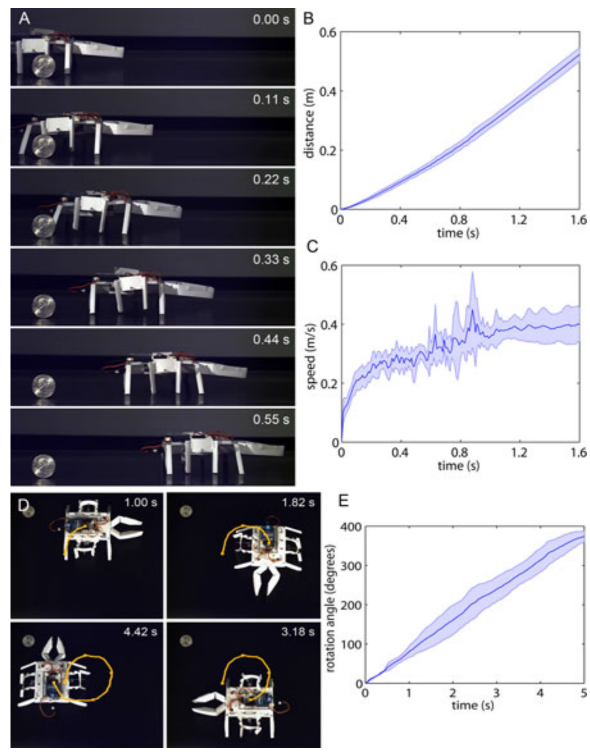

Fig. 6. Mobile manipulator performance characterization. (a) Sequence of six images from a high-speed video (filmed at 1000 frames/s) of the robot running on a rubber surface. The time of each frame elapsed since the first frame is indicated. This time interval was chosen to show the path of the robot's active legs during a full stride (although two strides were taken between each frame). (b) Mean distance travelled in a straight line by the robot as a function of time during five consecutive trials. The shaded region represents the standard deviation of the distance. (c) Mean and standard deviation of the instantaneous speed of the robot during the same five trials plotted in (b). (d) Sequence of four images (arranged clockwise from upper left) from a high-speed (1000 frames/s) video of the mobile manipulator robot executing a turning gait on a rubber surface. (e) Mean and standard error of the rotation angle of the robot with respect to time for five consecutive trials.

legs that rotate together (rock) in the transverse plane to perform a *rock-and-swing* walking gait [37] (see Video S5). The bodies are symmetric in the transverse and sagittal planes. SMA or microlinear servo actuators control each of the five degrees of freedom. When the center pair of legs is actuated to one side, they lift the front and back legs on the opposite side of the ground, allowing actuation of the near-side legs to propel the robot forward. The lifted legs simultaneously rotate forward in preparation for the next step when they will be lowered to the ground. To execute a turn, both sets of side legs swing in the same direction after rocking so that after one side pushes forward and the other pushes backward. Since the legs on each side always work in tandem, there are only three controlled degrees of freedom, which simplifies controller design.

Among these robots, we compared two options for actuation technology: 1) SMA coil actuators, which are compact, versatile, powerful, and silent; and 2) microlinear servo actuators, which offer robustness, efficiency, and higher actuation speeds. Thus, actuation technology as a design parameter can be set depending on task-specific performance metrics such as noise, lifetime, speed, or carrying capacity. SMA coils offer the advantage of being easily distributed over the body for localized actuation. However, they are inherently slow due to their reliance on heat transfer for each actuation cycle, and we found their performance to degrade over time. Prepackaged microlinear servos (SPMAS2000L, Spektrum RC) are faster and more consistent than SMA coils but have the constraint that they must be mounted to a body surface, requiring additional transmission elements.

The final two printable mobile robots in Fig. 4 utilize one active and two passive side legs on both sides of the robot. The active legs are actuated in a circular trajectory by two miniature-geared DC motors. As the active legs are lowered below the level of passive feet, they lift the passive legs up and push the body forward over half of their circular motion trajectory (see Fig. 6, Video S3). With this straightforward mechanism, the robot can achieve nonholonomic planar locomotion by adjusting the direction or speed of the two DC motors. Note that the two motors do not need to be phase synchronized for successful locomotion, which also reduced the burden on the electrical and control systems.

Robot prototypes are informed by the level of abstraction provided by (1)–(3). For the circular motion with radius r of the active feet to result in net forward locomotion, the four passive legs should bend less than r in the vertical direction. Formally, taking into account the angle of these legs with the vertical axis (45°), the total vertical deflection in the worst case should satisfy: $\delta = \mathrm{mg}/8k_b \leq r$. Inserting parameters for the present instantiation ($m = 45$ g, $k_b = 781$ N/m, and $r = 5$ mm), $\delta = 0.07$ mm, yielding a factor of safety of 71.

IV. Experimental Testing

We performed a series of experiments in order to test the capabilities of our prototype printed robots. We measured the gripping force of our printed end effector [see Fig. 1(a)], and used it to lift rubber sheets of various masses. The gripper weighed a total of 10.2 g, exerted a gripping force of 78.8 ± 3.0 mN, and lifted rubber weighing up to 14.5 g (see Video S4).

We implemented forward, backward, and turning gaits on the servo-actuated hexapod by altering the sequence of actuations (see Video S5). We measured the speed of the servo-actuated hexapod on a paperboard surface for two different gait periods, and with and without an 8 g payload. By running a microservo hexapod continuously on a paper surface using two 160 mAh lithium polymer batteries (in series), we found the useful lifetime of the robot to be 36 min. We also tested the ability of the servo-actuated hexapod to climb steps (see Fig. S2, Video S5). The robot was able to consistently climb steps with a height of 4 mm (approximately 10% of its body height). Finally, we measured the prototype's maximum payload by adding spare batteries to the front of the robots and additional weights on top (see Video S5). The servo-actuated robot carried a maximum total payload of 48 g (370% of body weight). The extremely lightweight nature of origami robots in conjunction with design rules to achieve rigidity and strength lead to this significant payload carrying capacity. The failure mode at larger payloads was that the added mass raised the center of gravity of the robot and caused it to tip over (see Video S5).

For better accuracy in the faster DC motor-actuated hexapod, we filmed the robot executing straight and turning gaits at 1000 frames/s with high-speed video cameras (see Fig. 6, Video S3). We also placed four small reflective markers on the back of the robot and used a motion capture system (VICON) to track the position and orientation over time. We first commanded the robot to run in a straight line along a rubber surface [see Fig. 6(a)]. We used MATLAB to extract and plot the mean and standard deviation of the distance travelled over time for five consecutive trials [see Fig. 6(b)]. The robot ran forward at an average speed of 410 mm/s (five body lengths per second). Large deflections in the unactuated legs indicate that elastic energy was being stored and released during the gait cycle. To obtain the linear velocity of the robot over time, we took the instantaneous derivative of the position data and smoothed the data using a moving-average low-pass filter with a span of five samples [see Fig. 6(c)].

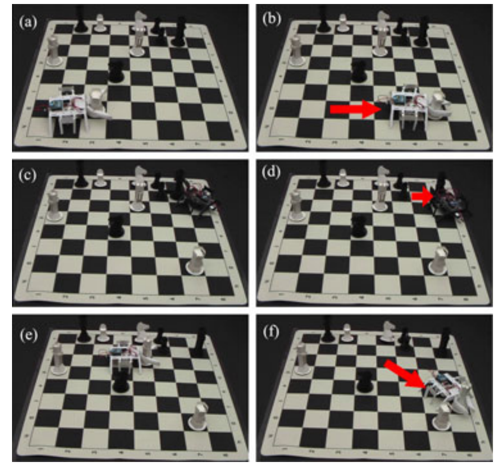

Fig. 7. Sequence of frames from a locomotion and manipulation experiment. (a)–(f) Remote controlled white and black printed robots take turns playing moves in a game of chess by grasping and dragging pieces on a chess mat without disturbing the surrounding pieces (see Video S1).

We then commanded the robot to execute on-the-spot clockwise turns [see Fig. 6(d)], and determined the mean and standard deviation of the yaw angle of the robot with respect to time for five consecutive experiments [see Fig. 6(e)]. Inplace turning trials showed an average turning rate of 79°/s. The average displacement of the center of the robot from its initial position after executing a 360° turn was 75 mm (smaller than one body length).

We demonstrated the ability of our ant-inspired legged robot design to grasp and manipulate objects by creating two copies of the robot and having them play a chess game by remote control (see Fig. 7, Video S1). The chess pieces used in this experiment were also fabricated from folded paper. This experiment demonstrates the manipulation and locomotion agility of the printable robots. The experiments also show their potential use for fetching objects for users with limited locomotion and mobility.

Finally, we analyzed the energy consumption of the printed, DC motor-actuated hexapod. The robot ran for 38 min on a single battery charge and its cost of transport (COT), a typical measure of locomotion efficiency, was 50.7 J/(kg · m). Fig. 8

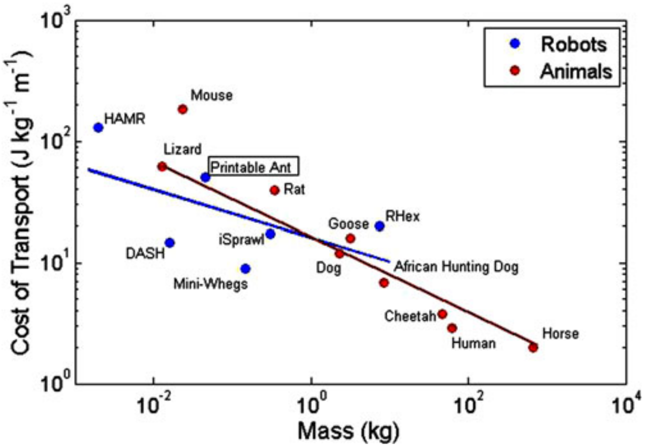

Fig. 8. COT versus mass for various legged robots and animals. Animal data adapted from [38], robot data from [39].

plots this value along with those of other legged robots and animals against mass. Our printable ant robot's COT followed the power law trend observed previously for legged animals [38]: Smaller animals expend more energy per pound for locomotion. Here, we note that this trend also holds true for legged robots, although with an exponent of smaller magnitude (-0.2 instead of -0.4).

V. Discussion

The results presented here demonstrate that our printable robotics approach to manufacturing can be used to rapidly fabricate low cost, capable, agile, functional 3-D electromechanical machines. While many of our fabrication steps (laminating, soldering) were performed manually in the lab, these steps could all be automated with currently available technology to create a robot printing machine that requires no technical knowledge or skill on the part of the user. Automated folders [40], or embedded folding actuators [7], [11], [12], could also be used to allow the printed robots to fold themselves. Furthermore, automated design techniques could then be employed to instantiate an existing template to a specific application or even compose existing designs to generate new functionality as we have shown here.

An exciting possibility with printable robots is the ability to design robotic systems with larger or smaller characteristic dimensions than those presented here. While the design and modeling approaches we have described are scaled well in both directions, the fabrication process would require adaptation. The resolutions of our fabrication tools and folding techniques limit the minimum feature size of our robot systems to the millimeter scale. For example, the CO_2 laser machining system we used had a cut width of $\sim$100 μm, limiting our minimum features to millimeter scale. More complex UV laser systems can cut similar materials with cut widths of $\sim$5 μm, reducing the minimum feature size by at least an order of magnitude [30]. Beyond this, nanofabrication techniques would need to be developed. Additionally, at very small scales, manual folding would no longer be an option and self-folding approaches would be required [11], [12].

In scaling up in size, materials would be the limitation. Eventually, (beyond $\sim$50 cm) the mass of the system would cause unacceptable deflections in the rigid sections. This could be solved with the use of stiffer materials for the rigid sections [10], [30], at the cost of increased laminate complexity. A hierarchical structure could also potentially improve the stability of larger structures.

We envision a wide range of applications for printable robots. In the near future, printed robot kits could be used in science, technology, engineering, and mathematics education. Low cost robots and manipulators printed on demand may be useful for remote procedures in medical and disaster relief applications. They can also be viewed as custom-built grasp-and-fetch tools for people with limited mobility or accessible consumer products [41] in general. Finally, their extremely low mass and volume when unfolded may make them useful for applications limited by payload mass and volume, such as space exploration.

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