Pop-up Mars Rover with Textile-Enhanced Rigid-Flex PCB Body

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Abstract— **This paper presents a novel manufacturing paradigm for constructing origami-inspired pop-up robots for future space exploration missions. The new approach uses a textile-enhanced rigid-flex printed circuit board (PCB) to implement a folding robot chassis using robust, spaceflight-tolerant materials, and integrates the robot electronics directly into the chassis for added compactness. The new approach also decouples the mechanical and electrical functions of the chassis flexures for improved kinematics and lifetime. This manufacturing paradigm was used to build PUFFER (Pop-Up Flat Folding Explorer Robot), a self-actuated pop-up rover being developed to provide a low-payload-cost mobility enhancement for future NASA missions.**

I. INTRODUCTION

Robotics has contributed tremendously to our understanding of our solar system and universe, taking us to places far beyond our own planet that could not be accessed by other means. To date, robotic space probes, landers, and rovers have sent back a wealth of remarkable imagery and data from Mars, Europa, and various small bodies, to name a few. With every mission, a multitude of new targets emerge as areas of interest for future investigation. The surface of Mars, for instance, has revealed a host of high-science-interest sites such as lava tubes, caves, and recurring slope lineae (RSLs). Similarly, flybys of Jupiter's moon Europa have revealed fascinating "chaos terrains" where the moon's liquid ocean may be interacting with the icy surface. A common theme across many of these new targets of interest is that they involve difficult terrain features that will present challenges to future robotic exploration. Accessing these science-rich extreme terrains will therefore require advances in robotic spacecraft mobility.

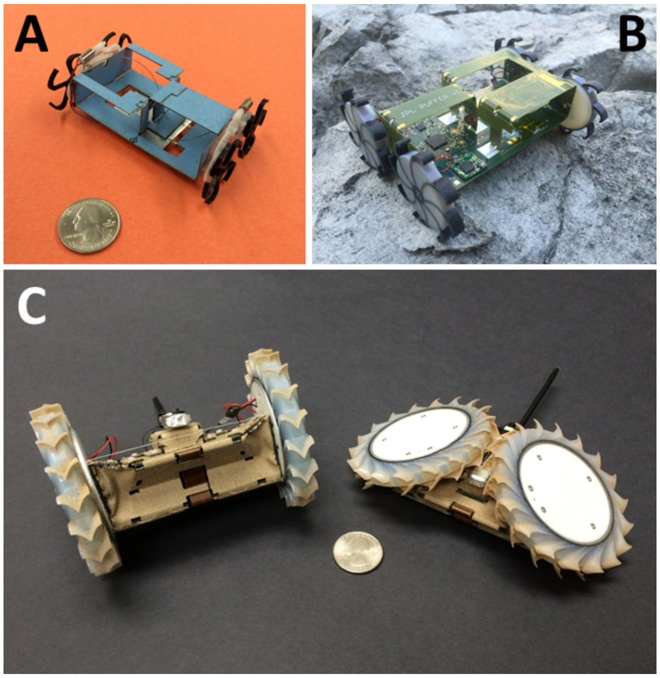

Fig. 1. Progression of PUFFER prototypes beginning with earliest (A) to latest (C), showing evolution of manufacturing paradigm towards more robust, spaceflight-tolerant materials. U.S. Quarter shown for scale.

To address the need for new robotic mobilty in space exploration, the NASA Jet Propulsion Lab (JPL) is developing PUFFER (Pop-Up Flat Folding Explorer Robot). PUFFER is a palm-sized, origami-inspired wheeled rover that is designed to accompany larger spacecraft on future missions, serving as a mobility enhancement to provide access to new terrains. The PUFFER rovers are constructed using a collapsible "pop-up" chassis, shown in Figure 1, that folds into a compact volume for stowage. This folding feature allows for low-payload-cost integration of multiple units on a parent spacecraft, such as a larger rover or lander. PUFFER's small size and folding chassis also provide unique mobility benefits that enable PUFFER to maneuver in extreme terrains inaccessible to the parent. For instance, PUFFER can partially collapse its chassis into a low-profile, yet maneuverable, stance for entering highly-confined spaces. This partial collapsibility can also be used to lower the platform's center of gravity for climbing steep inclines, as has been shown in past climbing robot work [1].

In future missions, when a parent spacecraft encounters terrains of interest that are better accessed with PUFFERs, it could eject one or more of the folded units, which unfold themselves on command. The parent then guides the PUFFERs into the new terrain, controlling them and receiving data from the instruments that they carry over a wireless radio. The parent spacecraft provides high-power communications with Earth. In this cooperative parent-child paradigm, the PUFFERs provide unique mobility in extreme terrains with no added risk to the primary mission.

This paper discusses work done in developing PUFFER

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for future Mars applications and presents a novel manufacturing technique for implementing robust, spaceflight-tolerant origami-inspired robots. This work builds on the well-established Smart Composite Microstructures (SCM) folding robot manufacturing paradigm [2], [3] used in the construction of numerous palm-sized robots such as RoACH [4] and DASH [5]. We present a new manufacturing approach for implementing these types of robots using textile-enhanced printed circuit board (PCB) technology and materials compatible with the Mars environment. This paper also presents new concepts in the mechanical design of pop-up robot structures and the integration of electronics onto these structures.

Our work here also relates to prior literature on the Pop-up Book MEMS robot fabrication paradigm [6], [7], where folding laminate structures are designed to pop-up for easier, higher-yield assembly of fine-featured robotic mechanisms. These laminate structures often employ printed circuit materials, enabling the direct integration of electronics onto the robot body. One-time pop-up assembly has been demonstrated using both external actuation (e.g. manually) [8] and with self-actuated shape-memory composite structures [9]. Later work has also demonstrated reversible forms of self-assembly and self-actuation using pneumatics [10] and micro-fluidics [11]. Our work focuses on using the pop-up structure concept to implement a repeatably collapsible body. This collapsiblity has implications on the folding structure design, particularly on robustness of repeatedly-cycled flexure joints, and we discuss how these are addressed through the new textile-enhanced rigid-flex PCB concept.

II. EARLY PROTOTYPES

Early PUFFER prototypes were designed using a basic pop-up structure with two interleaved four-bar linkages. Four thin-profile wheels were mounted to the sides of the linkages for mobility. When folded, the linkages collapse around one another, bringing the wheels in plane with the folded structure. When unfolded, the linkages flip the wheels into a perpendicular driving configuration. In these early prototypes, the pop-up structure was designed for one-time deployment, with the four-bar linkages unfolding through elastic energy stored in the structure and latching together with small magnets when fully upright.

A. SCM Proof-of-Concept

A proof-of-concept prototype, shown in Figure 2, was fabricated using the Smart Composite Microstructures process established in [3]. This early prototype used a simple posterboard-polymer film laminated structure, with the polymer film serving as the hinges for the pop-up structure and the posterboard providing the rigid sections. Nitinol wire was used to spring-load the opposing four-bar linkages, causing these to pop upright when the structure was released. Two pairs of small neodymium magnets were embedded in the structure at a location where they latch the opposing four-bars together in an upright configuration.

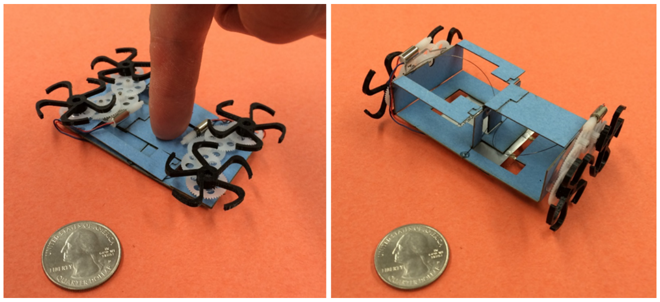

Fig. 2. First proof-of-concept PUFFER prototype, built using SCM fabrication paradigm. PUFFER is shown folded (left) and unfolded (right). Prototype had a mass of 13 grams. U.S. Quarter shown for scale.

Mobility was provided by four wheg-type wheels [12], with the left and right wheel-pairs driven by independent transmissions. The transmissions were constructed using 4 mm diameter brushed motors and acetal gears, both from Didel [13]. The motors were controlled wirelessly using a small remote-control receiver with integrated motor drivers [14]. Power was provided by a 90 mAh, 0.5 mm thick lithium-polymer battery. Both the battery and remote-control receiver were mounted flat against the bottom of the prototype.

B. First Rigid-Flex PCB Chassis

In order to begin transitioning to more robust, spaceflight-tolerant construction, the opposing four-bar structure was manufactured using a conventional rigid-flex PCB. Rigid-flex PCBs exhibit folding properties that are similar to those utilized in SCM-type folding robot structures. Implementing these robots from rigid-flex PCB chassis components is appealing since it allows the robot electronics to be integrated directly onto the robot body, allowing for a streamlined construction. Furthermore, polyimide-based flex and rigid-flex circuit boards have been flown successfully on numerous Mars missions, making them a promising manufacturing solution for PUFFER and other Mars-bound folding robots.

A first folding PCB, shown in Figure 3, was fabricated to evaluate the mechanical and electrical properties of rigid-flex joints in a PUFFER-type structure. This first iteration consisted of a two-layer flex circuit with stiffener material added to create the rigid board sections. The flex circuit was fabricated from a 50 micron thick polyimide substrate with 1 oz copper on both sides. 0.4 mm thick polyimide stiffeners were laminated to the bottom copper side of the flex circuit, leaving the top copper side exposed. A flexible soldermask was applied to the top copper side of the PCB. In order to reduce the flexure material thickness for increased compliance, no additional insulating layers, such as coverlay layers, were used.

In order to evaluate the cycle lifetime of copper traces passing over flexure joints, the first PCB iteration was fabricated with a variety of sample electrical trace configurations for cycle testing. As shown in Figure 3, straight, 0.4 mm wide copper traces were run over both short (0.8 mm width) and long (3.5 mm width) flexures, on both top and bottom

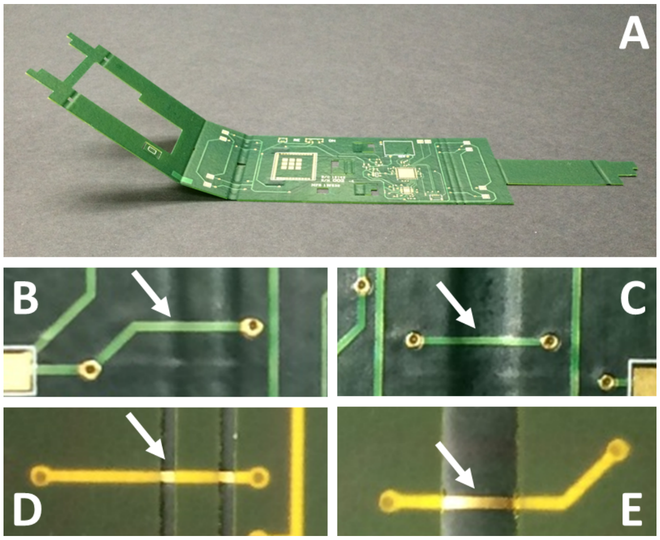

Fig. 3. First PUFFER rigid-flex chassis iteration, using conventional two-layer flex circuit with added stiffeners. Complete PCB shown in (A), with slight bend to illustrate location of flexures. (B) through (E) show the sample flexures that were cycle tested, with arrows highlighting specific location of bending: a short top side flexure (B); a long top side flexure (C); a short bottom side flexure (D); and a long bottom side flexure (E).

layers of the flex circuit. In these test articles, the traces on the bottom layer were always cycled in tension (outside of the flexures), while the traces on the top layer were always cycled in compression (inside of the flexures). Each of the four flexure trace configurations was cycle tested, at room temperature, over their full range of motion in the four-bar PUFFER structure (90° to 180°), measuring continuity along the traces over each cycle until a loss in continuity was detected. Two test articles were evaluated for each configuration, yielding the cycle lifetimes given in Table I. Although preliminary and not exhaustive, these cycle tests indicate a preference for longer flexure traces cycled in compression, with both articles of that configuration maintaining full continuity for over 1000 cycles, the maximum number tested. For context, 1000 cycles is an extremely conservative estimate for the number of cycles a PUFFER flexure would experience in a Mars application.

TABLE I

FIRST TRACE CYCLE LIFETIME RESULTS

Trace Configuration	**Article 1 (cycles)**	**Article 2 (cycles)**
Short flexure; Copper in tension	10	23
Short flexure; Copper in compression	120	100
Long flexure; Copper in tension	73	800
Long flexure; Copper in compression	>1000	>1000

C. Second Rigid-Flex PCB Chassis

Using the lessons learned from the first rigid-flex iteration, a second batch of folding chassis boards was designed and fabricated. This second iteration used the same stack-up as the first, a two-layer flex circuit with added stiffeners, but all flexures carrying electrical traces were designed as long flexures (3.5 mm), with the copper always passing over the flexure on the inside of the bend (loaded in compression). Cycle testing was carried out, again at room temperature, on 20 sample flexure traces, with all surviving 1500 cycles without failure.

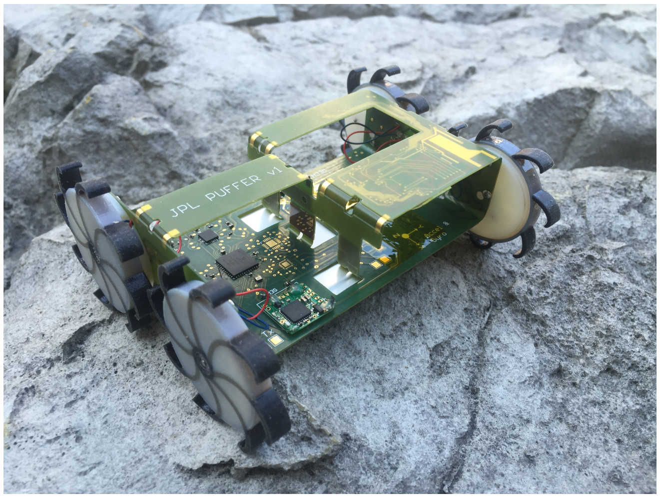

Fig. 4. First complete rigid-flex PUFFER prototype, built with PCB from second rigid-flex iteration. PCB was populated with a wirelessly-controlled motor driver circuit for driving the four independently-actuated wheels.

The second rigid-flex PCB chassis was designed with complete layout for a wirelessly operated motor controller, which was populated with components and assembled into a complete PUFFER prototype, shown in Figure 4. Like the first SCM-based prototype, this platform used four wheg-type wheels for mobility, but the wheel design was improved by packaging an independent motor and transmission inside each wheel hub. This improvement prevented dust and other environmental debris from damaging transmission components, a significant challenge when designing for the Mars environment. The size of the thin lithium-polymer battery was doubled over the previous prototype to 180 mAh, which provided a driving range of 400 m per charge on smooth flooring.

III. FLEXURE DESIGN CONSIDERATIONS AND CHALLENGES

Several mechanical and electrical design factors must be considered when implementing a repeatably folding robot structure using circuit board materials. One such consideration is in the mechanical design of the rigid-flex PCB joints. In order to replicate the hinge-like motion acheived in SCM designs, the corresponding flexures in the rigid-flex implementation need to be kept both relatively short and compliant. A typical SCM flexure has a length of less than 1 mm (rigid section to adjacent rigid section), and is implemented with thin, highly compliant materials such as 25 micron thick PET film [3]. Such short lengths and thin cross-sections are relatively uncommon in rigid-flex PCB manufacture, so design modifications were required when transitioning to a rigid-flex construction.

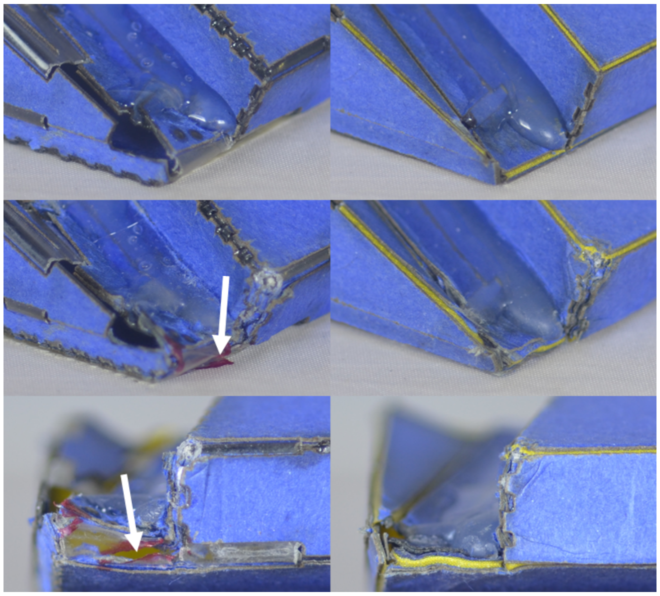

Fig. 5. Images of early impact testing on PUFFER chassis prototypes. Images on left show prototype with PET plastic film flexures, while images on right show prototype built with woven “Ripstop” nylon flexures. Top row shows prototypes prior to impact tests, while lower two rows show prototypes after 35 drops from 1 m height with 100 g added mass. The plastic film flexures experienced catastropic cracking (white arrows), while the woven material flexures remained intact.

Another key consideration is that of the lifetime of copper traces that pass over repeatedly cycled flexures. Since the flexure copper traces pass critical signals between adjacent rigid sections of the folding structure, it is imperative that these survive the number of flexure cycles expected over the life of the platform. Numerous factors will influence the lifetime of these traces, including copper thickness, copper geometry, and whether insulating coverlay layers are used. The greatest influence on lifetime, however, will be the bend radius of the traces, with longer flexures (larger bend radii) reducing stress on the copper. Here, the preference for longer flexures, when those flexures carry copper traces, trades off with the desire for short, hinge-approximating flexures discussed earlier.

A final design factor that needs to be considered is the mechanical robustness of the flexure material itself. The polyimide materials commonly used as flex circuit substrates propagate cracks readily, making thin polyimide-based flexures susceptible to tearing when subjected to loads. Various standard solutions exist for increasing the robustness of rigid-flex joints, such as the use of additional coverlay layers or glass weave reinforcements, but these will also increase the thickness, and therefore stiffness, of the joints. Here, increasing the robustness of conventional polyimide based flexures trades off with the desire for highly compliant hinge-like joints.

The first two rigid-flex iterations revealed a handful of limitations of conventional polyimide flexures when applied to the PUFFER concept. First, it is difficult to replicate the short hinge-approximating joints used in SCM designs with basic polyimide flexures carrying electrical traces since the traces do not survive sufficient cycles over such tight bend radii. The approach that was taken in these iterations, increasing flexure lengths and bend radii, increased trace cycle life but the resulting flexures exhibit undesired compliance and tended to produce structures with poor kinematics and folding. Another limitation of the conventional polymer-type flexures is their lack of robustness. Impact testing with prototype PUFFER structures revealed concerns with crack propagation through polymer-only flexures, shown in Figure 5. For comparison, these failure modes were eliminated when the same structure was prototyped using a “Ripstop” woven Nylon material for the flexure joints.

IV. TEXTILE-ENHANCED RIGID-FLEX PCB

In order to overcome the limitations encountered with the conventional rigid-flex PCB PUFFER prototypes, a novel textile-enhanced fabrication paradigm was developed. This new approach adds a textile layer to the rigid-flex PCB stack-up, as shown in Figure 6, and was used to successfully implement the latest generation of PUFFER prototypes. In these prototypes, the textile-enhanced approach enables a significantly more sophisticated pop-up structure with much-improved folding kinematics and substantially improved robustness.

A. *Textile-Enhanced Flexures*

Integration of a textile layer into the PCB stack-up allows the mechanical and electrical functions of the rigid-flex joints to be decoupled, overcoming the limitations observed in the conventional polyimide-only flexures. In the textile-enhanced paradigm, mechanical hinge-approximating joints are implemented using very short sections of the textile, while the electrical (trace-carrying) bridges are implemented with much longer, large bend radius polyimide flexures. As

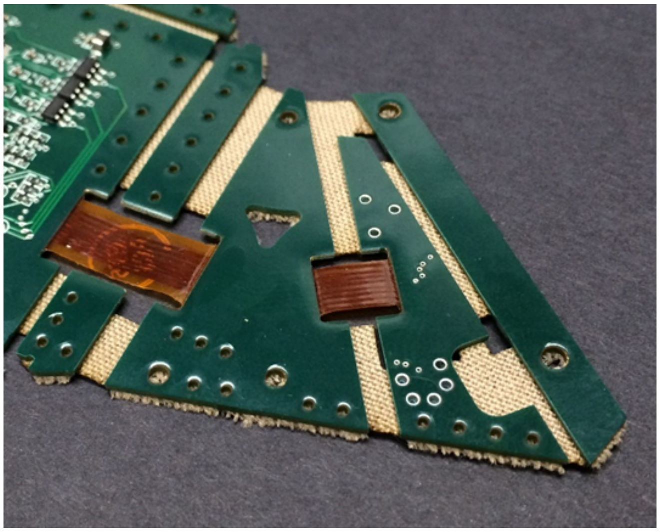

Fig. 6. Close-up of textile-enhanced flexures on latest PUFFER rigid-flex PCB. Short, hinge-like mechanical joints are implemented with the woven textile (beige material), while the electrical bridges (dark orange polyimide) pass in between these with gentler bend radii.

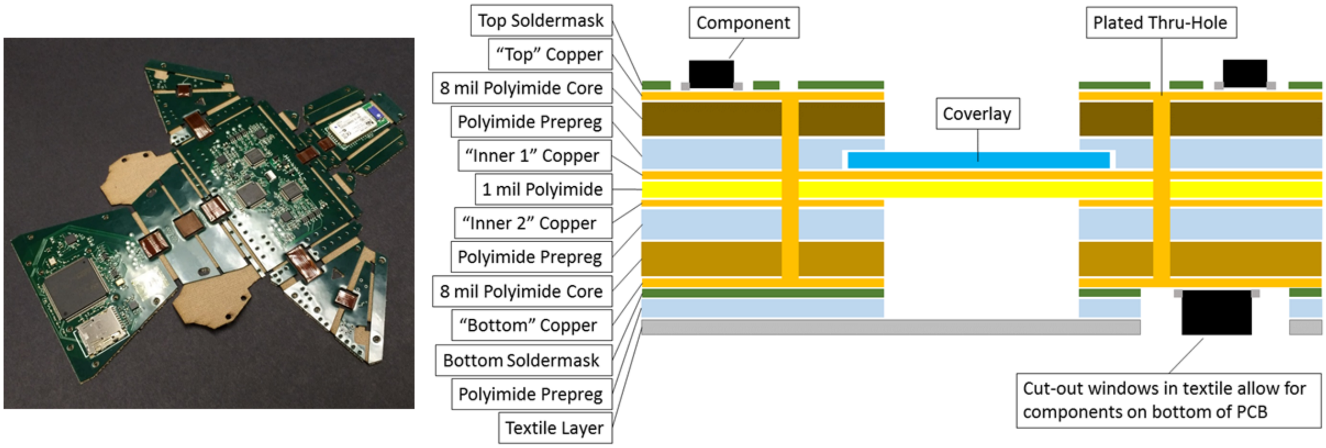

Fig. 7. Completed textile-enhanced rigid-flex PCB (left) with diagram of stack-up used (right).

shown in Figure 6, the electrical polyimide-based bridges that link rigid PCB sections are surrounded by the shorter textile-based mechanical flexures. Thus, the short mechanical flexures enforce the hinge-approximating kinematics of the joint, while the electrical bridge can pass with a much gentler bend radius to preserve trace conductivity over repeated cycling. A textile material was chosen as the additional mechanical joint layer due to the compliance and robustness of textiles, even in very short flexures [15]. Automated cycle testing, conducted at room temperature, of the three most stressed electrical bridges on the latest textile-enhanced PUFFER chassis revealed that these survive in excess of 5000 cycles over their full range of motion without loss of continuity.

B. *Textile-Enhanced PCB Manufacture*

A novel PCB fabrication methodology was developed for manufacturing the new textile-enhanced rigid-flex PCBs. A completed PCB, and its corresponding stack-up are shown in Figure 7. A 4-layer rigid-flex PCB is etched, laminated, and plated using standard manufacturing processes. A Nomex textile is then patterned on a laser cutter. This patterning exposes windows where the Nomex should not overlap with the polyimide electrical bridges, and in regions where components need to be mounted to copper pads on the bottom of the PCB, as shown in Figure 7. The patterned Nomex is then laminated to the 4-layer rigid-flex PCB with polyimide pre-preg material as a bonding agent. After bonding the Nomex, the entire stack-up is passed through a hot air solder level process to prepare the copper footprints for mounting components.

A Nomex weave was chosen as the material for the textile. Nomex is an extremely temperature resistant material, making it suitable for the high-temperature processing steps involved in the PCB manufacturing process. Nomex has also been used successfully on past NASA missions, for example in the landing airbags on the Mars Pathfinder and Mars Exploration Rover missions, making it a suitable material for an origami-inspired rover intended for future Mars applications.

V. LATEST TEXTILE-ENHANCED PROTOTYPE

The new textile-enhanced rigid-flex PCB technology was used to develop a more sophisticated PUFFER prototype than had been possible with the more conventional rigid-flex construction. The chassis, mobility features, and electronics are presented below, along with early mobility results.

A. *Chassis Mechanical Design*

The chassis is a 3D linkage that allows the robot to change its shape for improved mobility, smaller storage, and to position instruments. In particular, the chassis allows the robot to sprawl – to change the angle of its wheels relative to the ground. A high sprawl angle (i.e. wheels upright) makes it easier to go over rough terrain, while a low sprawl angle (i.e. wheels prostrate) makes it easier to climb up hills and to go under overhangs [16]. Besides improving robot mobility, the chassis also protects the insides of the robot from impacts due to the energy-absorbing compliance in the textile joints. Additionally, the chassis provides an enclosure that isolates the electronics inside the robot from the environment.

In terms of linkage design, the chassis consists of one planar four-bar linkage coupled to two spherical four-bar linkages. The planar linkage forms most of the chassis and the spherical linkages enclose the sides and tilt the wheels. The whole system has one degree of freedom in expansion.

Figure 8(a) shows a cross-sectional view of expansion as seen from the side of the robot. In this view, only the planar linkage is visible. Due to the short textile joints used, all unconstrained flexures are drawn as circular pin joints. All constrained flexures, those fixed during assembly, are drawn as rigid bends. The two expanding links at the front of the robot are kept from going completely vertical in the fully-expanded state through the kinematics of the design. This is to prevent the linkages from reaching a singularity, thus improving the impact-absorbing compliance of the structure.

Figure 8(b) shows a cross-sectional view of expansion as seen from the back of the robot. In this view, all three of the robot's linkages are partly visible. It must be noted that some of the spherical linkage joints are not normal to

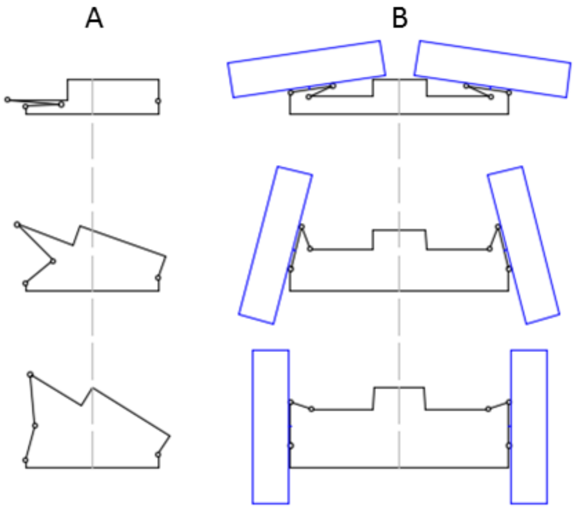

Fig. 8. Linkage diagram showing mechanical design of latest PUFFER chassis. Diagram shows chassis fully folded (top row), partially folded or sprawled (middle row), and fully unfolded (bottom row). Diagrams on left show the chassis cross-section from the side while diagrams on the right show the chassis cross-section from the back. Right column includes outlines of wheels, shown in blue. Dashed lines shows planes about which cross-sections were taken.

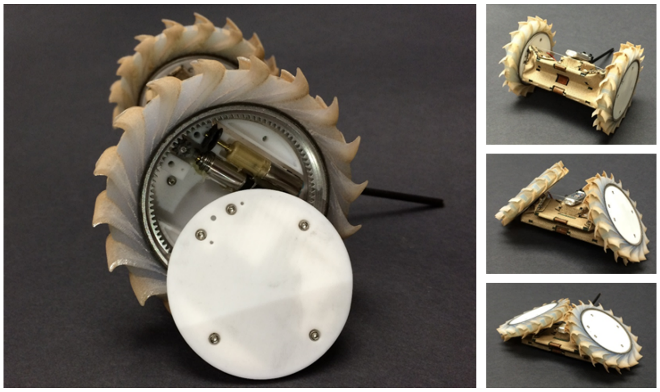

Fig. 9. View of wheel transmission with outer Teflon housing removed (left). Wheel contains two 6 mm diameter motors. The lower motor drives the aluminum wheel rim via an annular gear, while the upper motor drives a cable winch that pulls the wheels together to fold the chassis. A sequence of images of PUFFER folding itself is given in the column on the right.

the plane of the paper, so this cross-section is not uniform across neighboring planes through the robot. In particular, the three pin joints on either side of the robot intersect at the corresponding back corners of the robot, creating the spherical linkage. The linkages that mount the wheels at the sides are sized such that the sprawl angle of each wheel cannot exceed the range [0°, 90°]. The flexures that connect the wheel linkages to the base are normal to the plane of the paper, so the wheels always lie on parallel planes.

B. Mobility and Pop-Up Actuation

The mobility architecture for the latest PUFFER prototype consists of two independently actuated wheels and a passive tail. The two wheels allow the platform to maneuver in a skid-steer manner, where the passive tail counteracts the moment from the wheels to allow forward motion. This two wheel design presents several advantages over the four wheel approach used in the previous prototype. First, the latest platform can be flipped by driving the two wheels in reverse, where the tail cannot counteract the moment from the wheels. This maneuver is desirable for self-righting the platform in the event that it flips in adverse terrain. Other interesting capabilities have also been demonstrated with two-wheeled platforms, such as the ability to jump up stairs [17], [18] and climb a variety of steep surfaces [19], [20]. Another design advantage of the two wheel approach is that the wheels themselves can have a larger diameter, improving ground clearance. The larger wheels also house robot components that would impede folding if mounted elsewhere on the platform. In the case of the latest prototype, the wheels house the two drive motors (one motor per wheel), a pop-up actuation motor (in one wheel only), and also contain available volume for housing cold temperature tolerant batteries.

The two wheels consist of a thin aluminum rim that is driven by the independent drive motors over a round teflon housing. The teflon housing attaches to the folding chassis and anchors the drive motors to form the transmission at the center of each wheel. The teflon housings also provide a bearing surface for the aluminum wheel rims to rotate against, thus eliminating the need for ball bearings. In the current prototype, different wheel treads can be attached over the aluminum rim for mobility testing.

In addition to providing mobility, the current wheels also actuate the pop-up function of the current prototype. This is accomplished through the use of a winch-type mechanism embedded in one of the wheels. The winch consists of a 6 mm diameter motor that spools a cable. This cable runs between the two wheels and, when tensioned, pulls the two wheels together and folds the chassis. When tension is released by unspooling the cable, return springs attached to the folding chassis restore it to an upright position. In the latest prototype, the return springs are implemented using thin Nitinol ribbons that push the chassis sides away from the chassis base. These Nitinol return springs have survived extensive cycling through ambient-temperature lab and field testing, and future work will identify the appropriate alloys for use in a space environnment.

C. Electronics

The electronics design on the latest PUFFER prototype chassis provides wireless communications, motor control, and navigation camera functionality. For communications, the prototype has a RN-41 bluetooth radio module mounted near the top of the folding structure. Motor control is provided by a brushless DC (BLDC) motor driver circuit, as well as a stepper motor driver circuit. For sensing, the latest prototype includes circuitry for capturing images from an OmniVision OV9655 CMOS camera. All of the subcircuits are connected using the polyimide electrical bridge

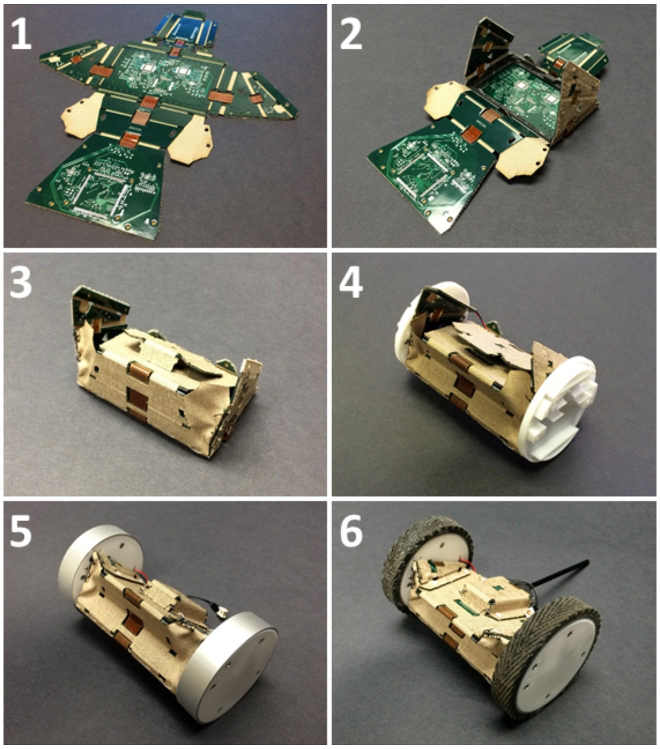

Fig. 10. Assembly of latest rigid-flex PCB into PUFFER prototype. Images show: (1) flat rigid-flex PCB prior to assembly; (2) attachment of base frame and return springs; (3) stitching of textile flaps; (4) attachment of wheel housings; (5) assembly of complete wheels; and (6) closing of structure with plastic rivets.

connections in the flexures and are controlled by a 32-bit STM32F427 microcontroller. The prototype is designed to run from two 300 mAh Lithium-Polymer (LiPo) batteries, connected in series. In ambient temperature field testing, the prototype was able to traverse 625 meters of level dirt trail on a single 250 mAh, 2S LiPo battery.

D. Assembly

The assembly process for turning a textile-enhanced rigid-flex PCB into a PUFFER prototype is shown in Figure 10. The process begins with a flat rigid-flex PCB (step 1). A low-profile 3d-printed plastic frame is then stitched onto the chassis base using drilled holes designed into the PCB, and Nitinol ribbons are bolted between the chassis side flaps and base (step 2). The purpose of the plastic frame is to enforce a slight offset above the chassis base to accomodate the height of electronic components that get mounted there. Next, the two loose textile flaps are stitched onto the side flaps to form the front of the folding chassis (step 3). At this point in the assembly, the teflon wheel housings are bolted onto the side flaps (step 4). The wheels are then assembled (step 5), and the remainder of the chassis is joined together using plastic rivets (step 6). At this phase of development the plastic rivets are removable, to have access to the robot's internals.

E. Initial Mobility Testing

The latest PUFFER prototype has undergone early mobility testing, shown in Figure 11, with promising results. Prototype specifications are given in Table II. In the fully expanded configuration, the platform has 2.5 cm ground clearance. The rover can turn using skid-steering and can flip by reversing the wheels. The winch actuator in the wheels can drive PUFFER into a folded or sprawled state, where the wheels are splayed out and the body is compressed. The platform is 7.5 cm tall when fully expanded and 4 cm fully folded. The sprawled configuration provides mobility benefits in addition to a smaller storage volume. The platform can drive in partially-sprawled configurations under obstacles as low as 4 cm. The angled wheels in the sprawl position prevent PUFFER from flipping. This allows the platform to back up out of confined spaces, without requiring space to turn around. The sprawled configuration also improves slope climbing ability. With wheels parallel and coated in solid, treaded rubber tires, the latest prototype can climb a 35° plywood slope. By sprawling the wheels, it can drive up a 40° slope. Examples of current PUFFER mobility are provided in the video supplement for this paper.

TABLE II
LATEST PROTOTYPE SPECIFICATIONS

Specification	**Value**
Mass	150 g
Expanded Dimensions	10 cm (L), 7.5 cm (W), 7.5 cm (H)
Folded Dimensions	14.5 cm (L), 7.5 cm (W), 4 cm (H)
Maximum Ground Clearance	2.5 cm
Slope Climbing	40°
Minimum Overhang Access	4.0 cm

VI. CONCLUSION

The textile-enhanced rigid-flex PCB paradigm presented in this paper provides a new approach for implementing origami-inspired robots for spaceflight applications. This manufacturing paradigm allows origami-inspired planar mechanisms to be transitioned to robust, spaceflight-tolerant materials, and overcomes the limitations observed in convential rigid-flex implementations. Specifically, the inclusion of a textile layer decouples the mechanical and electrical functions of flexures, allowing joints to exhibit both tight, hinge-like folding kinematics as well as gentle bend radii for conductive PCB traces. As demonstrated in this paper, the textile-enhanced PCB concept enabled the design

Fig. 11. Latest PUFFER prototype shown folded into a sprawled configuration to fit beneath a rock (left) and climbing a 20° slope (right).

and construction of a sophisticated folding chassis, with integrated electronics, for the latest self-folding PUFFER prototypes.

VII. FUTURE WORK

Future work will focus on improving the novel forms of mobility enabled by the self-folding chassis, and field testing in Mars-analogue environments. In particular, work will focus on ascending steep inclines using a low-profile sprawled configuration and accessing confined spaces beneath rock overhangs, both of which are of significant interest for future Mars extreme terrain exploration.

Future work will also investigate solutions for transitioning the current generation of terrestrial PUFFER prototypes into units that can tolerate environmental factors such as the low temperatures and high radiation levels experienced on Mars. Rigid-flex PCBs have been used extensively in past Mars missions, and design techniques learned there will be applied to the PUFFER layout. Unlike past NASA Mars rovers, the PUFFER folding chassis does not support the use of a warm, radiation-shielded enclosure for electronics. Instead, future work will address these factors at a component level, transitioning to cold- and radiation-tolerant electronics, motors, and batteries, all of which are currently under development.

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