Robotic origamis: self-morphing modular robots

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Abstract— **Programmable matter is a material that produces distinctive shapes or patterns according to a given command. Often they are composed of interconnected modular elements that are able to make or break the connections or alter relative orientation. We present programmable matter based on robotic origami that demonstrates the capability to fold into 3D shapes starting from a nominally 2D sheet. This concept requires high torque density actuators, flexible electronics and an integrated substrate. We report on unique robot fabrication techniques that incorporate torsional shape memory actuators and stretchable electronics.**

I. INTRODUCTION

Intelligent materials that can change physical state by specific commands are known as programmable matter [1], [2], [3]. Robotic origami is a functional robotic form of programmable matter that can reconfigure into various 3D shapes from its initial flat configuration. The system consists of a network of tiles connected with compliant joints and folding actuators. The tiled body is composed of flexible and rigid sections that enable the robot to attain arbitrary shapes [1]. Creating functional programmable sheets - with applications ranging from manipulation to locomotion - from quasi-2D parts has its engineering challenges in the areas of computation, fabrication, material selection and design. Optimization software tools need to be developed for robot specification, design, and fabrication. Multi-material fabrication procedures within the required dimensions and scales need to be accomplished. Novel materials that embed joints, sensing, actuation, computation, and connectors need to be developed to fabricate the robots. We have developed robotic origami (self-folding sheets) that can self-morph into multiple shapes [4]. Ultimately, a functional robot requires structural integrity to achieve a wide range of tasks and we aim to elucidate solutions to different lines of research to meet technological and integration challenges in materials (for example, rigid and stretchable sections of the robot) and suggest a new paradigm in robot development, enabling rapid creation of new robots by reducing design and fabrication time. Here we present an overview of the fabrication techniques involved in the development of origami sheets.

II. ROBOTIC ORIGAMI CONSTRUCTION

Novel fabrication methods are needed to build and integrate actuators, electronics, and a multi-material body similar to the robotic origami in Fig. 1 [4]. The current choice of body material is fiberglass tiles due to its high strength-to-weight ratio, ease of machining, and compatibility with silicone based elastomers. The folding actuator is a custom designed shape memory alloy (SMA) sheet machined and annealed into a torsional actuator [5]. The low profile of the SMA torsional actuator conforms to the initial and final shape the robot. To accommodate compound folds [4] of the structure (i.e. folds several layers thick), it is critical for the joints to remain stretchable for creation of complex topologies. However, joints must also carry conductors to maintain electrical connectivity amongst the tiles; therefore, novel approaches to stretchable electronics must also be explored.

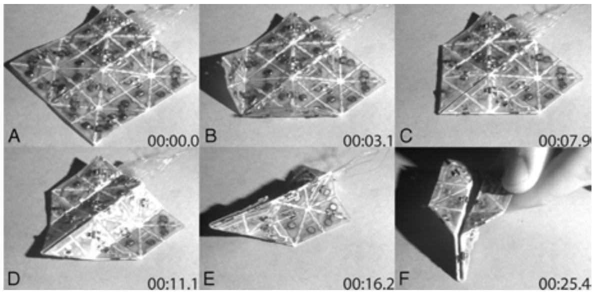

Fig. 1. 32-tile self-folding sheet, capable of achieving two distinct shapes [4]: a "paper airplane" and a "boat". Flat sheet prior to folding (A). Four-actuator group controlling flaps activated (B). Magnets for the first fold engaged (C). Remaining actuators are activated (D). Final shape (E) and inverted (F).

A. Modular origami sheet: interconnected tiles

From [1], a 'universal' geometry for producing diverse 3D morphologies from a 2D sheet is a set of interconnected triangular modules called a box pleat. The triangular tiles of robotic origami are base units of a morphing structure where the orientation change of the connecting joints dictate the final shape. Therefore, it is imperative to have direct control of the joint angles using folding actuators. Our sheet design maintains flexible joints when not activated and imposes a high torque on selective joints when the actuators activate. In order to introduce such opposing characteristics, we use different materials with contrasting stiffnesses: resin impregnated fiberglass sheets (s-glass) for the tiles, and thermoplastic polyurethane elastomer ($76\mu m$ American Polyfilm 70 shore A, polyether polyurethane) for flexures. The s-glass tiles are made of resin cured glass-fiber that is layered to have a cured thickness of $300\mu m$. We laser machine holes for magnets (used to lock shapes in place once folded) before curing the s-glass tiles. Once the magnets are placed with appropriate polarity, the s-glass sheet is cured in an oven at 140°C for 4 hours. Cured s-glass material is light (density of approximately $1.6 g/cm^3$) and stiff and easy to laser machine fine features. We laser-cut triangular

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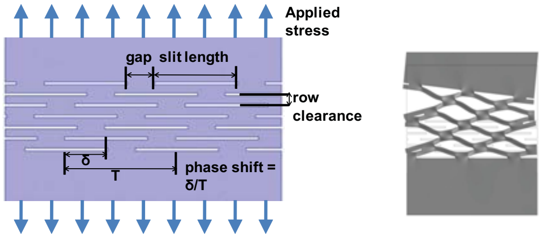
(a) (b) (c) (d) (e)

Fig. 2. Construction of 32-tile self-folding sheet: layered resin-impregnated s-glass with laser-machined magnet holes (a). Cured s-glass after inserting magnets and laser machined tiles (b). Etched and laser-machined copper circuit layer (c). Tiles with embedded copper circuit layer within polyurethane covering (d). Close-up view of the completed tile ready for actuator mounting (e).



(a) (b)

Fig. 3. Description of slit design parameters (a), COMSOL model of a deformed slit (b) [9].

tiles with actuator and circuit attachment features, and the excess material is removed while the tiles remain temporarily bonded on a steel shim backing to maintain relative positions. The tiles are covered with a thermoplastic polyurethane elastomer, vacuum bagged, and put in an oven at 140°C for 30 min. The vacuum bag ensures bonding between the s-glass surface, folding edges, and the rest of the exposed area. The cooled and bonded s-glass tiles can be carefully removed from the backing. Depending on the circuit type, additional circuits can be directly applied to the opposite side before infusing and closing in the s-glass layer between the polyurethane coverings. Figure 2 show steps in constructing a base origami sheet with flexible joints.

B. *Stretchable electronics*

The robotic origami requires highly stretchable circuitry that expands with the folding edges. There are continuing research effort in stretchable electronics [6], [7], [8], but still challenging to integrate into the robotic origami (when folded multiple times, strain reaches nearly 100%). We developed stretchable circuitry using a simple fabrication process and which enables easily modifiable circuit parameters [9]. The circuits have a low profile (sub-millimeter) and can be "printed" as an independent circuit layer onto the existing tiles. One solution of creating a stretchable circuit is by creating a transversely deformable pattern in a copper sheet. Copper clad kapton ($0.03mm$ Cu and $0.01mm$ kapton) is often used for conventional flex-circuit fabrication. Using the same material, we created a mesh pattern in the sections that experience the most strain. Different geometric patterns produce varying expandable structures which convert axial stress from compound folds into local bending moments. While keeping the gap, the row clearance, and the slit length constant, we varied the "phase shift" as defined in Fig. 3(a) in order to maximize the overall deformability of the circuit. The final slit pattern has 75% phase shift ($40\mu m$ row clearance, $100\mu m$ gap, and $300\mu m$ slit) that produces the highest elongation, and thus greatest compliance to stretching, to design the circuit [9].

In order to produce the copper circuit layer, we use a partial lithography process. After covering copper with a positive photoresist (Shipley SP 24D) and curing, the outline of the circuit is dry etched by raster-machining the area with a DPSS micro-machining laser to expose the insulator (kapton). When submerged in ferric chloride, the exposed area etches to leave only kapton. Once rinsed, we put the circuit again under the laser to machine meshes in the sections that fold. It is important to post-process the meshes as the wet-etching process is aggressive and less controllable for micron-scale features. When the mesh is complete, introduced in the right sections, the whole circuit is cleaned with acetone to remove any cured photoresist and finally rinsed with water to be used as a circuit layer.

C. *Actuators*

The actuators for self-folding robotic origami must be low-profile ($<500\mu m$), produce folds up to 180° and be easy to manufacture and integrate with the tiles. The most recent effort in SMA actuators is introduced in [5] with the addition of an external heater in order to avoid the high currents typically associated with Joule heating. The heater is specifically designed for the actuator by having a conforming shape and tuned resistance to thermally activate the actuator. A specific heater pattern has been designed on a Ni alloy 600 sheet (Dupont Kapton KH) which is dry-etched and wet-etched to construct the heater, and then insulated and attached to the SMA actuator (Fig. 4). This method has a rapid reaction rate compared to Joule heating the actuator material. The z-shaped actuator produces torsional movement about the folding edge upon activation and produces blocked torque of up to $3.5mNm$. The actuator is attached to the finished tiles with embedded circuits using bolts with a thread diameter $0.5mm$. The electrical connections are soldered to the electrode pads of the copper circuit (exposed sections from polyurethane).

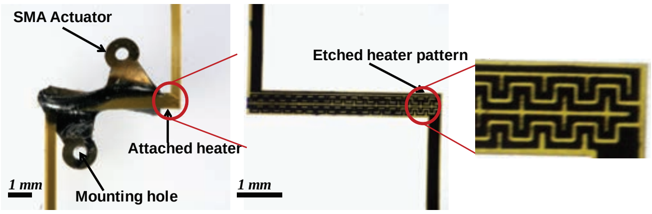


Fig. 4. Actuator module with an external heater. Insets show the custom designed micro-heater and its etched pattern [9].

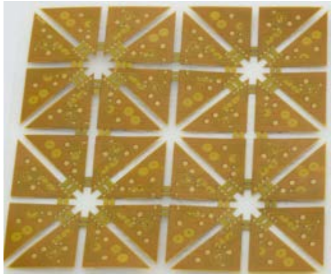


Fig. 5. Universal circuit sheet is commercially made with a conventional flex-circuit production process using acrylic coverlay, kapton, and fiberglass stiffener. Although it lacks flexibility in its mechanical properties, these sheets are mass producible and "programmable" for fast prototyping.

D. Universal circuits

Due to the characteristic of the layering process of the current robotic origami fabrication, each sheet has a unique circuit routing pattern that programs certain actuators to activate for a given shape sequence. The circuit routing "program" is embedded in the layers of the polymer sheet and once the actuators are attached, the sheet operates according to the programmed sequence and pattern. To test various types of shapes, a new routing design is required, making each sheet unique. For larger scale fabrication (quantity and size), we have designed a universal circuit, that can be used for all shapes in the given dimensions. There are two ways of creating a universal circuit using multiple vias. We can connect all the vias to share a common routing and then program the sheet by removing undesired connections. Inversely, we can make a universal circuit by having common vias but having no connection between the actuating points; to program, the required connections can be post processed via conventional reflow methods using a solder mask and solder paste. Figure 5 shows a prototype of a universal circuit that shares all the routing. To program, we physically alter the route pattern by laser machining. With the universal circuit, we introduce another level of "programmability" such that the desired shapes can be selected as a post-processing steps which alters the routing of the circuit layer.

E. Results

Using a described fabrication processes, we designed and tested 32-tile robotic origami. The programmed origami creates two shapes (table and pinwheel) from two different groupings of actuators (Fig. 6). The table shape requires 12 actuators and the pinwheel requires 16 actuators in total. Each set of actuators draws 1-3W depending on heating profile of the actuator (more current is drawn in the initial heating of the actuators). We used a custom-made microcontroller that applied 10Hz PWM signal to drive the actuators. Depending on the operating sequence, we modified the timing and the duty cycle of input. We observed that the actuators remained robust up to 50 cycles after which 2 out of 12 actuators started to fail.


(a) (b)

Fig. 6. Two programmed shapes of a robotic origami, table (a), and pinwheel (b).

III. CONCLUSION

In the effort of proving the concept of self-morphing robotic origami, we have presented a complete process of designing a functional sheet. The latest fabrication techniques, actuator design and effective stretchable circuit solutions have improved difficulties associated with multi-material, multi-step and serial processes in creating an origami sheet. The newest actuator modules display increased repeatability and robustness in performance and integration. We believe the post-programmable universal circuit sheet can further improve the fabrication process of robotic origami by minimizing fabrication steps.

IV. ACKNOWLEDGEMENTS

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