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Self-assembling Sensors for Printable Machines

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***Abstract*— Self-assembled structures and machines can be made using origami-inspired manufacturing methods. In particular, self-folding of two-dimensional materials using shape memory polymers and embedded electrical circuits has been utilized to build robots and structures in an inexpensive and rapid manner. In order to build increasingly complex and functional self-folding machines, however, methods for interaction with the environment are necessary. This paper presents and characterizes three types of self-folding sensors: a mechanical switch, a capacitive contact sensor, and a velocity sensor. We utilize specialized fold patterns to create cyclic mechanical linkages as well as additional composite layers such as magnetic sheets to build these sensors. We demonstrate the integration of two of these sensors, the switch and the contact sensor, into a lamp that can self-fold and immediately begin responding to its surroundings.**

I. INTRODUCTION

Origami-inspired manufacturing techniques can create complex three-dimensional structures from planar materials through methods that are inexpensive and rapid. With the aid of computational geometry [1], [2], arbitrary fold patterns can produce complex three-dimensional structures. Applications of folding techniques appear in paper actuators [3] and springs [4] as well as in programmable structures [5], piezoresistive force sensors [6], and robots [7], [8]. Pop-up book MEMS is an additional technique that enables the self-assembly of complicated three-dimensional mechanisms and millimeter-scale robots from two-dimensional composite materials [9], [10].

Because of their low cost and speed, origami fabrication methods can be used as a new type of printable manufacturing. While 3D printing enables the rapid manufacture of custom prototypes in industry and research labs [11], folded machines can offer additional advantages such as decreased material usage and the ability to be stored or transported in two-dimensional form [12], [13]. However, as these machines and structures become more complex and the number of folds grows rapidly, it becomes increasingly difficult and time-consuming to fold these structures manually. Enabling such structures to self-fold can reduce the time and effort of building complicated machines from two-dimensional materials.

In order to automate the assembly of machines, self-folding has been assimilated into two-dimensional manufacturing methods. This provides the potential for autonomous machine assembly and deployment. One particular method combines shape-memory polymers (SMPs) and additional composites into thin laminates. Self-folding is induced via resistive heating circuits, triggering contraction of SMP layers along fold lines [14], [15], [16]. Prestretched polystyrene (PSPS), an inexpensive SMP that can shrink up to 50% bi-directionally when heated above about 95° C, is well-suited for inducing the self-folding of various structures and devices [17]. However, beyond geometry and structural properties, one important aspect of self-folding machines is the ability to sense and interact with the environment.

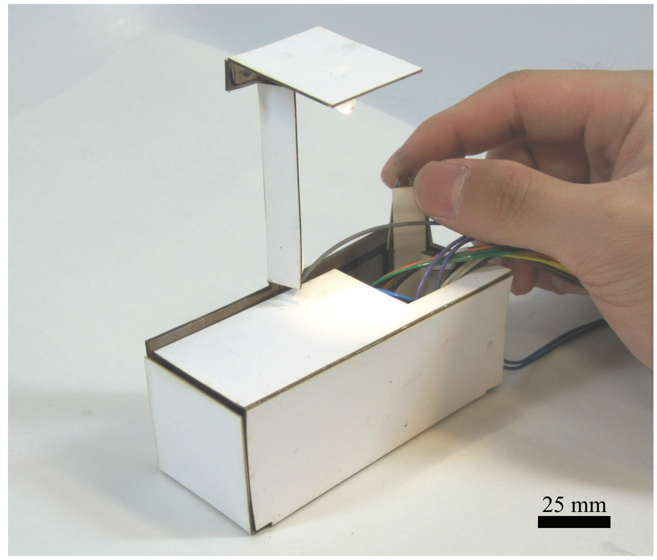

Fig. 1. A self-assembled lamp operated by both a mechanical switch and by a capacitive contact sensor. The lamp was fabricated as a two-dimensional composite of paper, copper-polyimide, and prestretched-polystyrene. After folding was induced by sequential application of two amperes of current to resistive circuits, the lamp could be turned on and off by the switch or the contact sensor.

There are countless extant sensors, made by more traditional means, that can measure properties such as contact or touch, proximity and distance, force, velocity, temperature, and pressure. Furthermore, sensors may utilize a variety of structures or methods to accomplish similar capabilities. For example, mechanical contact switches may take the form of latches [18], pushbuttons [19], and mercury switches [20]. Force can be measured by the displacement of a spring [21] or a change in capacitance between two conductive plates [22], [23]. Velocity can be measured with optical components and analog electronics [24]. However, the majority of such sensors are built with traditional manufacturing and assembly methods, are often complex and expensive, and are usually incompatible with the printable manufacturing process (other than as discrete components).

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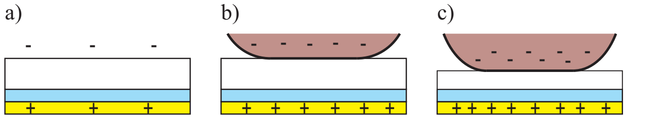

Fig. 2. The capacitive sensor consists of a copper plate (yellow) and a dielectric layer consisting of paper (white) and tape (blue). (a) The capacitance between the plate and the air is small. (b) When a finger comes close to the capacitive sensor, the total capacitance increases. (c) When the finger applies pressure to the sensor, the paper dielectric layer compresses, increasing the capacitance further.

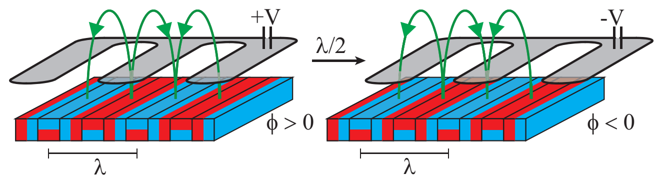

Fig. 3. An illustration of the mechanism for the electromagnetic velocity sensor. A Halbach array contains permanent magnets whose adjacent magnetic dipoles are rotated 90° from one another, creating a strong alternating magnetic field on one side of the array. The sensor loop is shaped periodically with a spatial period λ to match the period of the alternating magnetic field. As the sensor moves across the top of the sheet, an alternating magnetic flux occurs through the copper loop, and a proportional voltage is induced. In the top figure, the total flux through the sensor is ϕ. When the sensor moves a distance $\lambda/2$, the magnetic flux is now $-\phi$.

In this paper we present three types of sensors integrated into the self-folding manufacturing process developed by Felton et. al [15]. We have developed a capacitive contact sensor, an electromagnetic velocity sensor, and a bi-stable mechanical switch by adding additional composite layers into the manufacturing process, incorporating features into the existing layers and flexible printed circuit board (PCB), and by designing specialized fold patterns that form complex mechanisms. Furthermore, we integrated two of these sensors, the switch and capacitive contact sensor, into the structure of a self-folding light-emitting diode (LED) lamp (Fig. 1), demonstrating the efficacy of these sensors for integration with rapidly manufactured self-folding machines.

II. Design

The sensors we have developed build upon a printable manufacturing technique that utilizes two-dimensional layered composites and sequential folding triggered by supplied current [15]. In order to build printable sensors that can be incorporated into this autonomous two-dimensional manufacturing process, we utilize a combination of new mechanisms and additional composite layers.

A. Capacitive Contact Sensor

We designed a contact sensor that consists of an embedded copper pad included in the flexible PCB layer [15]. The capacitance C of two parallel plates is given by:

$$C = \varepsilon \frac{A}{d} \tag{1}$$

where ε is the relative permittivity, A is the area of overlap between the plates, and d is the distance between them. Without the presence of a second plate, the capacitance is between the plate and the surrounding air or environment (Fig. 2a). When a second conductive surface, such as a human finger, approaches the first, there is a measurable increase in capacitance (Fig. 2b).

The printable sensor consists of a capacitive plate on the same PCB as the resistive heating circuits used to actuate folding of the structure. The dielectric material consists of one layer of silicone tape and one layer of the paper substrate used for support. In addition to detecting contact between the finger and the dielectric material, we can measure the applied force of a finger as the capacitance changes according to the distance between the two conductive surfaces, the copper pad and finger. When force is applied, the dielectric compresses, acting as a spring whose displacement is proportional to the applied force. Assuming constant area of overlap between the two capacitive surfaces, we have a proportional relationship between force and capacitance (Fig. 2c).

B. Velocity Sensor

We designed a velocity sensor that utilizes electromagnetic induction to translate velocity into a measured voltage signal. Faraday's law of induction states that the voltage V of a closed loop of wire present in a magnetic field is given by:

$$V = -\frac{d\phi}{dt} \tag{2}$$

where

$$\frac{d\phi}{dt} = \frac{dB}{dt} A \tag{3}$$

and ϕ is the total magnetic flux through the wire, B is the strength of the magnetic field, and A is the total area of the loop. We can induce a voltage by changing the strength of the magnetic field periodically.

We used a sheet of magnetic material arranged in a Halbach array similar to that found in many refrigerator magnets. A Halbach array is an array of magnets bonded together such that adjacent magnetic dipoles are rotated 90° from each other. This produces an alternating magnetic field on one side of the array with a spatial frequency $\frac{1}{\lambda}$. A conductive loop of copper was fabricated with serpentine coils running parallel to the magnetic poles and spaced at the same frequency over the surface of a Halbach array sheet. When the coils are positioned directly over the northern poles of the magnet, the magnetic flux is at a maximum. When the loop moves a half-period perpendicular to the poles, the coils are then directly over the southern poles, and the magnetic flux through the loop is equal but opposite (Fig. 3). When the loop moves relative to the magnetic array, the magnetic flux oscillates between the maximum and minimum flux, and a voltage is induced in the loop. We assume that

$$B = C \sin\left(\frac{2\pi}{\lambda} x\right) \tag{4}$$

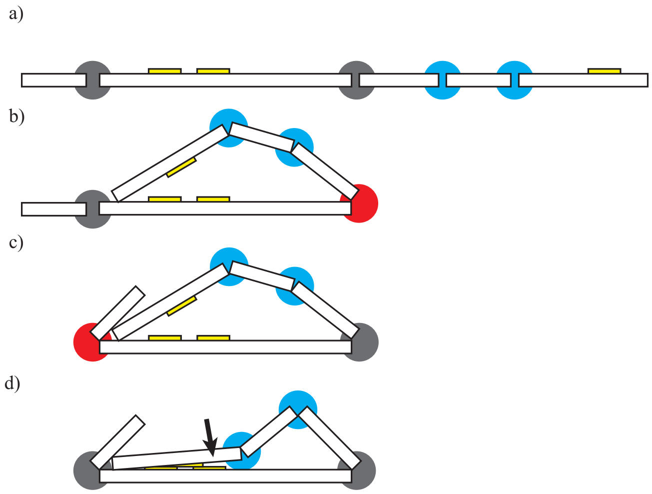

Fig. 4. The folding process of the cyclic four-bar linkage used in the switch design. Blue hinges indicate passive hinges and gray the folding hinges. The yellow locations indicate the contact points of the circuit. (a) The linkage in planar form. (b) The linkage folds over on itself. (c) A trapping fold pushes the links in place, creating a bi-stable mechanism. (d) The linkage in its closed position. The yellow contact surfaces on the two links that pinch together are held in place by the stiffness of the links and flexures.

and the velocity v is a constant so that

$$x = v \cdot t \quad (5)$$

where C is the maximum strength of the magnetic field and x is the relative distance traveled between the sensor and the magnet. Differentiating eq. (4) with respect to x and combining with eqs. (2), (3), and (5) results in

$$V = -C\frac{2\pi}{\lambda}\cos\left(\frac{2\pi}{\lambda}vt\right)\cdot Av \quad (6)$$

with

$$S = \frac{2\pi}{\lambda}CA \quad (7)$$

where the period and amplitude of the induced voltage V are both proportional to the velocity v, and S is defined as a signal coefficient with units $\frac{mV\cdot s}{m}$.

We designed a trace pattern that matches the spatial frequency of the magnetic field to maximize the induced voltage that could be measured. By creating one movable structure with the loop of wire and one stationary structure with the magnetic sheet on it that constrains the movable structure to a single degree of freedom, we can measure the relative velocity between the two.

C. Bi-stable Switch

We developed a self-folding bi-stable switch based on a four-bar linkage design for bi-stable compliant mechanisms [25], [26]. The switch is self-assembled, utilizing sequential, trapping folding to create a cyclic linkage containing two passive hinges (Fig. 4). After folding and subsequent cooling of the SMP, the now-static fold provides a restoring force which is present even at the bi-stable points. This produces constant contact between the two surfaces of adjacent links, which can then be used to close an electrical circuit. The dynamic hinges allow this four-bar linkage to move. The switch is actuated by applying a force to overcome the energy barrier of moving between the two stable states (Fig. 4d).

D. Self-assembling lamp

To demonstrate the utility of self-assembled sensors, we created a self-folding lamp that incorporates a contact sensor as a switch and a touch sensor to adjust the brightness of the light. A folding pattern was developed to incorporate the designs of the two sensors into the flexible PCB layer, creating one continuous folding structure. To adjust the brightness with the capacitive touch sensor, an Arduino microcontroller was used to measure the capacitance and control the voltage output to the LED circuit.

III. Fabrication

The self-folding devices in this paper were all fabricated using methods consistent with those published in Felton et al. [15]. The two-dimensional composites consist of a layer of 510 μm paper substrate (Cold Press Bright, Epson), one or two layers of 18 μm copper circuits on 25 μm polyimide (AC181200R, DuPont), and a layer of prestretched polystyrene (PSPS) (Grafix Inkjet Printable Shrink Film, Grafix). The capacitive sensor was built using these three layers (Fig. 5a). The contact switch and lamp required an additional circuit layer underneath the heating circuit for an additional current path controlled by the switch. After printing solid-ink circuit patterns onto copper-clad polyimide, the circuits were etched to remove excess copper using a ferric chloride etch tank. The paper and PSPS layers were cut using a CO_2 laser cutter (VersaLaser 2.0, Universal Laser Systems), aligned along with the circuit(s) using pin alignment, then bonded together with 50 μm double-sided

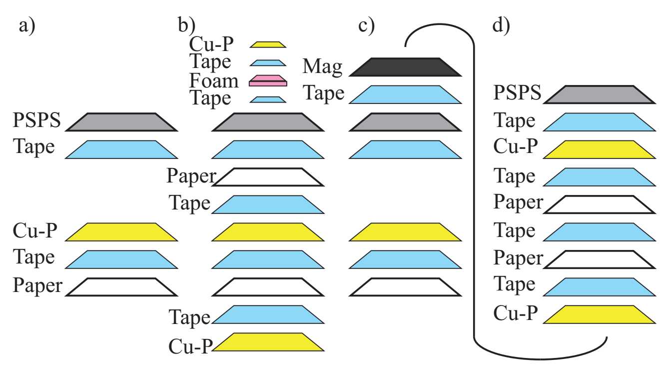

Fig. 5. (a) The capacitive contact sensor consists of three layers: the PSPS, copper-polyimide circuit, and paper substrate layer. (b) The contact switch adds an additional copper-polyimide layer underneath the PCB, containing a disconnected circuit, as well as a small piece of foam and copper to bridge the break in the circuit. There is also another layer of paper between the heating circuit and PSPS to utilize the paper as a lever arm [15]. (c-d) The velocity sensor is made up of two separate layers: the sensing layer and the support layer. (c) The support structure of the velocity sensor consists of the normal laminates of PSPS, the PCB, and paper with an additional magnetic sheet layer on top. (d) The sensing layer consists of PSPS, a copper-polyimide PCB, a paper layer, a second paper layer, and the sensor loop etched from copper-polyimide. It has two paper laminates: one to fold into a handle and one to provide structure to the sensor loop.

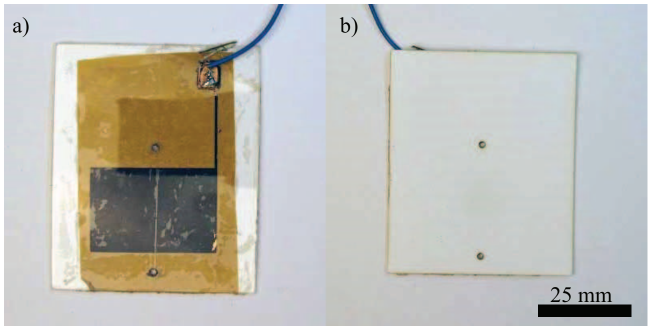

Fig. 6. (a) A bottom view of the capacitive contact sensor. The copper pad (black) was integrated into the existing flexible PCB layer that is used to induce folding. (b) The top view of the capacitive contact sensor.

silicone tape (ARclad 7876, Adhesives Research). Wires and other discrete components (e.g. the white LED used in the lamp) were manually soldered to the composite prior to folding.

The velocity sensor is composed of two separate components: a sensing layer containing the loop of copper in which voltage is induced and a support layer that wraps around the sensing layer after folding to restrict the sensor's movement to one degree of freedom. The sensing structure consisted of, from top to bottom, an SMP layer, a heating circuit layer, two layers of paper, and a sensing copper-clad polyimide layer which contained the loop where voltage was measured (Fig. 5c). We used one layer of paper to provide structural rigidity to the copper-polyimide loop on the bottom and a second to provide rigidity to the handle that folded up. The support structure also contained a magnetic sheet (12 mil Flexible magnetic sheeting, Magnum Magnetics) manually cut and bonded to the top of the PSPS layer with silicone tape (Fig. 5d).

The bi-stable switch had an extra layer consisting of a small piece of copper-clad polyimide and a piece of foam, which were bonded together and on top of the SMP layer (with silicone tape, prior to fold actuation) at the specific point where the contact would bridge the gap in an exposed copper circuit (Fig. 5b). The foam, due to its softness, allowed for the switch to more reliably maintain contact with the circuit. An additional paper layer was inserted between the PSPS and PCB to act as a lever arm and increase the folding torque. The lamp was fabricated in the same manner as the switch, but with a different fold pattern and shape.

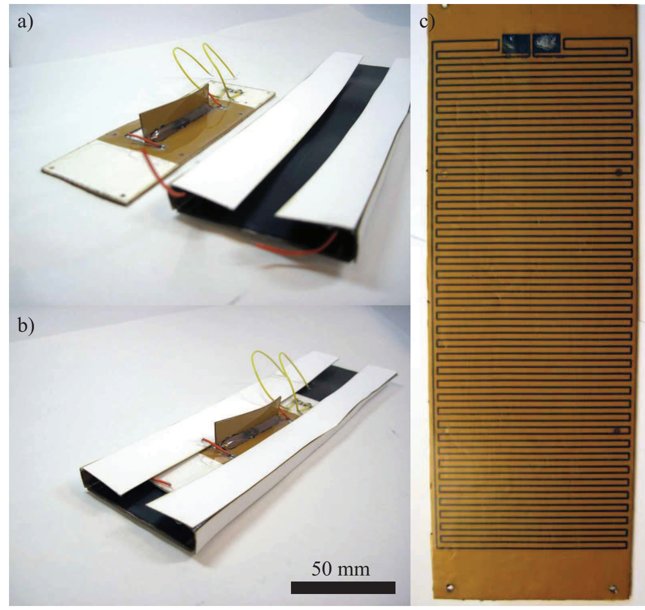

Fig. 8. (a) A self-folded velocity sensor. (b) The sensor layer and support layer are separate layers, but folded together in one process, as the support layer folds over the sensor layer to constrain its movement. (c) A bottom view of the sensor structure of the velocity sensor. The loops have spatial frequency λ to match the frequency of the magnetic field, maximizing the measurable voltage signal induced in this wire.

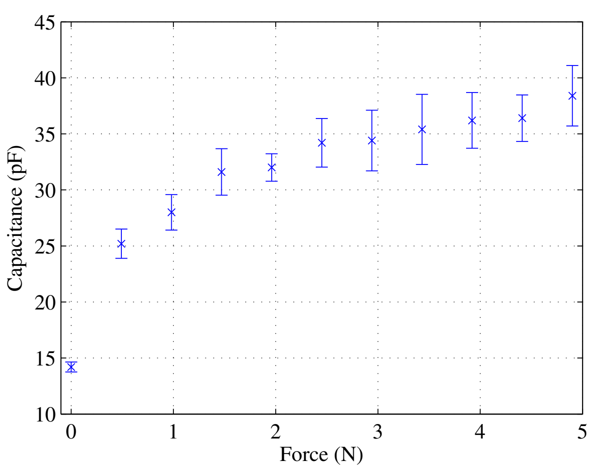

Fig. 7. (a) The measured capacitance as a function of applied force. Measurements were taken at 0.5 N intervals between 0 and 5 N. After initial contact, the relationship is approximately linear. Five sample measurements were taken at each force. The error bars represent one standard deviation from the mean.

IV. Evaluation

We measured the capacitance of a standalone contact sensor (Fig. 6) under varying amounts of force using a surface-mount device tester (18910, Aven). We applied force through a finger in increments of 0.49 N and measured the sensor output. The sensor registered a noticeable jump in capacitance when a finger touched the surface of the sensor, and also demonstrated changing capacitance as more force is applied. We applied 0 to 5 N to the surface of the sensor and measured the capacitance, and the results demonstrate an approximately linear relationship after initial surface contact of 0.49 N (Fig. 7).

The velocity sensor successfully self-folded after supplying the circuits with two amperes (Fig. 8). In order to measure the voltage produced by the sensor, we amplified the signal from the sensor with an operational amplifier (LM741, Texas Instruments) circuit with a gain of 459.33 and measured using an Arduino. We moved the sensing structure across the magnetic support structure at variable velocities and measured the corresponding alternating voltage signal,

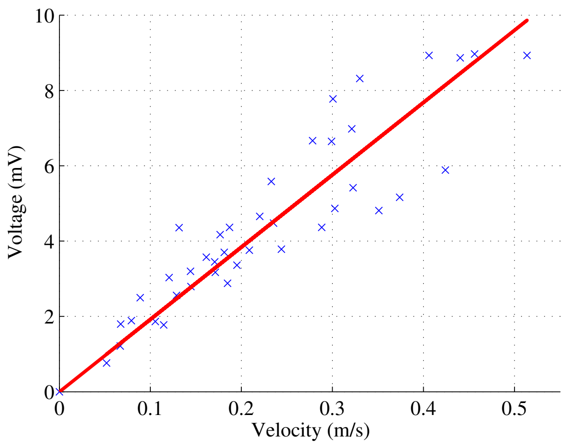

Fig. 9. The measured voltage from the velocity sensor as a function of velocity. The relationship is approximately linear with an R^2 value of 0.8234.

recording the highest measured amplitude of the signal. The velocities were measured via video recording (See Supp. Video).

We measured the voltage output of the sensor at velocities from 0 to 0.5 m/s, which varied in amplitude from 0 to 9 mV. The measured voltage signal data displayed an approximately linear relationship with the velocity and was characterized by $V = 19.2v$ with an R^2 value of 0.8234 where the voltage V is in mV and velocity v is in m/s (Fig. 9). The measured signal coefficient S was thus $19.2\frac{mVs}{m}$.

A standalone bi-stable switch was built in order to demonstrate the ability for the switch to self-fold. Two amperes were supplied to the circuit sequentially, allowing the linkage to successfully fold over on itself (Fig. 10).

The lamp, which included both the mechanical switch and the contact sensor, successfully self-folded into the intended structure (Fig. 11). The bi-stable switch was tested as a

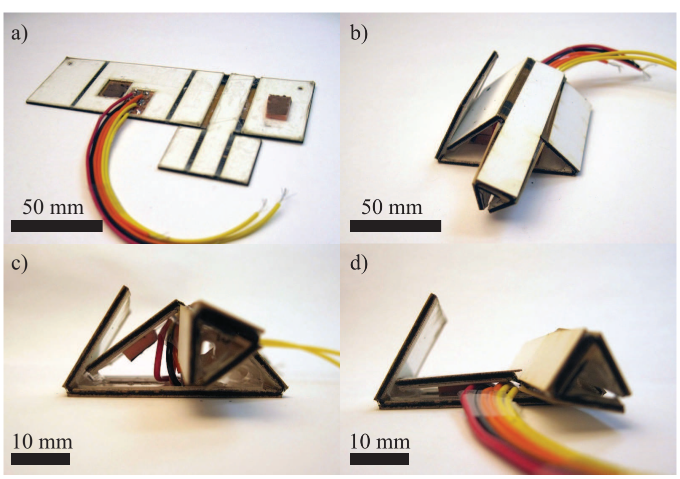

Fig. 10. (a) Two-dimensional planar form of the contact switch before self-folding and (b) after self-folding. (c) The cyclic four-bar linkage mechanism of the contact switch in its open circuit position and (d) in its closed circuit position. The foam helps maintain contact between the copper bridge and the broken circuit.

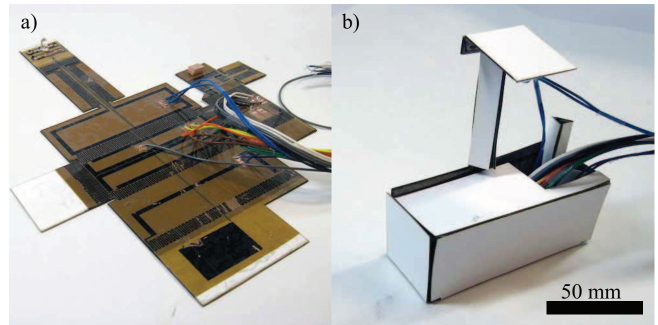

Fig. 11. (a) The planar configuration of a lamp before self-folding. The lamp incorporates the mechanical switch design and a capacitive contact sensor. (b) A completed self-folding lamp.

component of the lamp by flipping it manually and observing the completion of the LED circuit. The switch turned the lamp on 156 consecutive times, and was successfully flipped a total of 335 out of 350 times. To adjust the brightness of the lamp based on the capacitive contact sensor, an Arduino microcontroller was used to measure the capacitance and control the voltage output to the LED circuit (See Supp. Video). The capacitive sensor also successfully turned the lamp on and off (See Supp. Video).

V. Discussion

The capacitive contact sensor successfully detected the touch of a human finger and demonstrates the potential to measure applied force. Because the measured range of capacitance is very small, however, the signal is still susceptible to noise such as nearby conductive objects and other electronic devices, and may not be suitable for detecting forces smaller than one Newton. However, a more compliant and thicker dielectric material may be able to provide a greater range in capacitance and thus more precise force measurements. We also demonstrated here that capacitive sensors can be readily integrated into the existing PCB layer. Further applications of this type of capacitive sensor can include a positional sensor or touchpad by combining multiple capacitive copper surfaces in a line or a lattice pattern to measure the location and amount of force of a touch. A second mobile capacitive surface may be added as an additional layer in order to measure position or velocity. Capacitive sensors embedded in the structure may also be applied for detecting fold angles and providing feedback during assembly into a three-dimensional structure. This may provide a useful tool in automating the self-assembly process.

The velocity sensor demonstrated the ability to self-fold two-dimensional structures that incorporate magnetic fields and materials. The predicted signal coefficient S was $98.3\frac{mVs}{m}$ given a measured magnetic field value of 9.2 mT at the surface of the magnetic sheet, an area of the surface enclosed by the copper loop 2720 mm^2, and a spatial frequency λ of 1.6 mm. The difference between the measured signal coefficient S of $19.2\frac{mVs}{m}$ and the predicted signal coefficient is likely due to an error in the measurement of the spatial frequency λ and/or the fabrication of the loop with frequency

λ. A slight difference between the actual frequencies of the magnetic sheet and the loop may result in a very large reduction in flux through the wire loop because of the alternating nature of the magnetic field, resulting in destructive interference. Additionally, the amplitude of the magnetic field may not have been constant along the surface of the magnet, and the sensor may not have stayed level with the surface of the magnet. Further work may involve building an accelerometer changing amplitude as well as frequency to accurately determine acceleration. Making the entire sensor smaller would allow for easier integration and use in self-folding machines, but this would require a stronger magnetic field and/or more precise fabrication methods.

The contact switch self-folded and successfully performed its function of turning a circuit on and off. Its design allows for easy integration into the design and fold patterns for more complex machines that may require bi-stable switches, actuators, or valves. However, there are geometric constraints such as a minimum width of the links in order provide sufficient torque from the SMP to actuate self-folding of such devices. Each self-folding hinge must be approximately 10 mm long or folding will not occur, limiting the total minimum size of the mechanism.

The self-assembling lamp demonstrates the potential for the rapid and inexpensive production of self-folding machines that can interact with the environment. It showed that even complex mechanisms, such as the mechanical switch, can be integrated into the self-folding process of a larger machine, and utilized in practical electronic circuits. Although printable sensors may lack the robust structural strength and reliability of other sensors, they have many potential applications such as low-cost rapid prototyping and manufacturing of customized designs in residential homes. The development of sensors that utilize self-folding manufacturing techniques and their integration into more complex structures is an important stepping stone in the path towards autonomously assembling machines and robots.

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