SPIN (Self-powered Paper Interfaces): Bridging Triboelectric Nanogenerator with Folding Paper Creases

Christopher Chen[1] **David Howard**[1] **Steven L. Zhang**[2] **Youngwook Do**[3] **Sienna Sun**[4]
Tingyu Cheng[3] **Zhong Lin Wang**[2] **Gregory D. Abowd**[3] **HyunJoo Oh**[1,3]

[1]School of Industrial Design [2]School of Materials Science and Engineering [3]School of Interactive Computing [4]School of Literature, Media, and Communication

Georgia Institute of Technology, Atlanta, GA, USA
{chrischen, davidhoward, stlzhang, youngwookdo, sienna.xsun, tcheng32, zlwang, abowd, hyunjoo.oh}@gatech.edu

ABSTRACT

We present Self-powered Paper INterfaces (SPIN) combining folding paper creases with triboelectric nanogenerator (TENG). Embedding TENG into paper creases, we developed a design editor and set of fabrication techniques to create paper-based interfaces that power sensors and actuators. Our SPIN design editor enables users to design their own crease pattern by changing parameters, embed power generating modules into the design, estimate total power generation, and export the files. Then following the fabrication instructions, users can cut and crease materials, and assemble them to build their own interfaces. We employ repetitive push-and-pull based embodied interactions with the mechanism of paper creases and demonstrate four application examples that show new expressive possibilities applying different scales of embodied interactions.

Author Keywords

Self-powered tangible interface; paper interface; paper electronics; TENG (Triboelectric Nanogenerator).

ACM Classification Keywords

Hardware~Sensors and actuators; Hardware~Tactile and hand-based interfaces; Hardware~Emerging interfaces; Hardware~Emerging tools and methodologies

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INTRODUCTION

Folding paper produces a crease, composed of two rigid faces and a connecting joint. Repeated folds across a single sheet generates tessellation crease patterns which provide mechanical properties that enable the motions of compression and expansion. This functional and aesthetic nature of paper folding has inspired diverse applications across architectural design, fashion design, mechanical engineering, biomedical engineering, and beyond. The inspiration from paper folding also has enriched the field of Tangible User-Interfaces. From animating paper folds [20,22,28,36] to sensing deformation of paper forms [32,35,40], HCI designers and researchers have demonstrated tools and techniques to create tangible interfaces that integrate the delicate materiality of paper with computing technologies. While prior works demonstrate seamless integration of sensing and actuation with paper, the challenge of connecting an external power source to those paper interfaces remains.

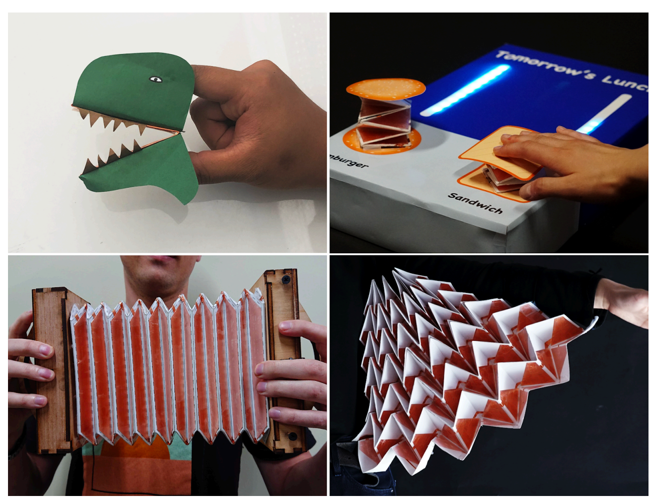

Figure 1. Self-powered Paper Interface Examples

This paper presents a set of fabrication techniques and a design software to create Self-powered Paper INterfaces (SPIN). We integrate the aesthetic and functional traits of paper creases with triboelectric nanogenerator (TENG) technology [12,37,39]. TENG is adapted from recent progress in material science, which supports energy harvesting: it produces triboelectricity through the assembly of paper-like, thin, lightweight and flexible materials such as polytetrafluoroethylene (PTFE) sheets. Attaching PTFE and copper layers on paper for each side of a fold and making repetitive contact generates triboelectric charges that we harness to operate sensors and actuators. We implemented a design editor that enables users to select a crease pattern from a library, adjust parameters to design their own crease, apply TENG(s) into the crease design, estimate the power generation calculated based on the TENG integration with the selected crease pattern, and export the files of each layer. Then the fabrication techniques support incorporating the TENG structure in the paper creases to create a self-powered paper interface, which employs repetitive motions of compression and expansion to harvest energy as a part of interactions.

We envision a future paper interface which blends a power source and electronic components while still maintaining the materiality of paper. In this paper, we present the following contributions:

- Fabrication techniques to create self-powered paper-based interfaces adapting TENG technology to the context of folding paper creases;
- A design editor that supports parametric design of crease patterns with TENG structure implementation, estimating power generation and exporting digital files;
- Application examples that show how the SPIN editor and fabrication techniques provide a new form of expressive possibilities that engage push-and-pull based embodied interactions in scale.

In the remainder of this paper, we first review related work and introduce the essential building blocks to create Self-powered Paper Interfaces. Next, we present the design editor that supports planning and generating digital files and describe the fabrication workflow. Then, we demonstrate four application contexts and describe how we apply the editor and fabrication techniques. Finally, we conclude with a discussion of limitations and future research directions.

2. RELATED WORK

2.1 Sensing and Actuating Paper

We can explore paper by cutting, bending, and folding or printing and painting on it. This rich affordance has enabled the seamless integration of sensing and actuating technologies to create paper-based tangible interfaces. For low-cost rapid prototyping of functional devices with paper, Kawahara et al. presented employing inkjet printing with conductive ink. It expands the potential in developing functional electronic devices on paper-based substrates [14]. By applying the inkjet printing technique, researchers also demonstrated sensing 1D and 2D flexing surfaces [35] or sensing geometries’ own physical cuts [40]. Diverse actuation methods also enhance interactions, especially adding dynamic movements to the static nature of paper. Researcher attached shape memory alloys (SMAs) [15,25,28], shape memory polymers [24,36], pneumatic actuators [20] or servo motors [23] to apply motions to paper-based artifacts. Some other methods to actuate paper include compositing with magnetization materials controlled by the external magnetic fields [11,22]. Inspired by the previous work on combining paper with sensing and actuating technologies to push the boundaries of paper as a tangible interface, in this paper, we focus on integrating energy harvesting technology with paper foldings and demonstrate it in connection with off-the-shelf electronic components.

2.2 Harvesting Energy by Triboelectric Nanogenerators

As conventional power sources suffer from limited capacity, short lifetime, and heavy weight, researchers have turned towards ways of harvesting renewable energy from human bodies and the living environment. Recently, many different energy harvesters have been developed which utilize mechanical energy, such as through electromagnetic [4] or piezoelectric [16] methods. Our work applies recent material science studies that generate energy by utilizing the triboelectric effect [12,37,39] to the unique expressive traits of paper creases. Triboelectric nanogenerators (TENGs) can convert mechanical energy into electricity efficiently based on contact electrification and electrostatic induction, and have gained attention to act as a new green and sustainable power source [38], as it could harvest energy from wind [43], ocean waves [46], and human body motions [17,45]. These nanogenerators have advantages of being low cost, robust, and easily to manufacture. Recently, researchers have demonstrated TENG using commercial and inexpensive materials such as paper, conductive ink, and Teflon tape [42] and integrated TENG with papercrafting techniques. Yang et al. [44] present slinky TENGs that harvest mechanical energy from human actions by a folded slinky structure and convert it into electricity. Likewise, Wu et al. [41] implement TENG systems, but in the context of kirigami to develop a stretchable structure. HCI researchers investigate employing the triboelectric effect to create self-powered systems and applications such as a printed book [13], light installation [10], microphone [3], or deformable cord sensor [34].

2.3 Expressive and Functional Papercrafts

We follow the notion of building electronics in the context of crafting with material properties [7]. Blending circuits with traditional sketching and crafting techniques on paper, researchers present novel ways to create more expressive and functional paper-based artifacts [6,18,19,29,30]. Subsequent research on possible applications include a broad spectrum of output devices from a pop-up book [27], a speaker and a lamp [33], personal health monitoring devices [1], and a tangible memory notebook [9]. These collectively reinforce the vision of integrated approaches across paper as both a low and high fidelity material, traditional paper crafting skills, and building circuits and embedding interactions. In this paper, we combine building energy harvesting technologies with paper folding techniques and present application examples that demonstrate a unique expressivity enabled by the combination.

3. SELF-POWERED PAPER INTERFACES

The SPIN project applies fundamental work on TENG, which is explained in detail in [12,37,39] and comprises a set of fabrication techniques with a software editor to combine TENG with folding paper creases. We use the electric charge generated from SPIN to run sensors and actuators and make the embedded circuit self-powered without external power sources. Figure 2 illustrates the composite structure of folded paper and the energy harvesting structure made of copper tape, PTFE, and optionally nylon sheets to improve the efficiency. The mechanical properties of paper creases afford the repetitive motions of compression and expansion to produce triboelectric charges. This action is a key element of the operation principle in using the TENG, which we will explain in the following section.

We create a self-powered paper interface with three building blocks: self-power module to harvest energy, form module to shape a crease, and function module to apply interactions.

3.1 Self-Power Module: Triboelectric Nanogenerator

SPIN operates on the basis of a contact mode triboelectric nanogenerator as the self-power module; its working mechanism is shown in Figure 3. At the initial state, PTFE and nylon layers are separated.

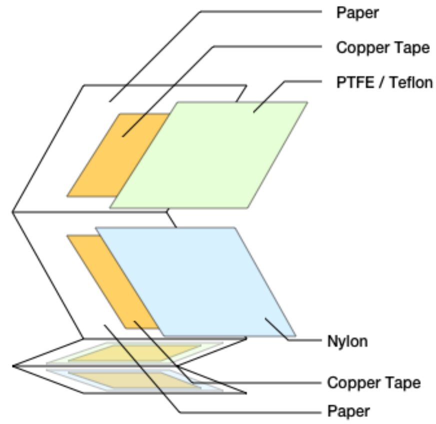

Figure 2. SPIN design: one unit of the energy harvesting structure is formed with a pair of two composite faces. Each side is attached to a paper crease.

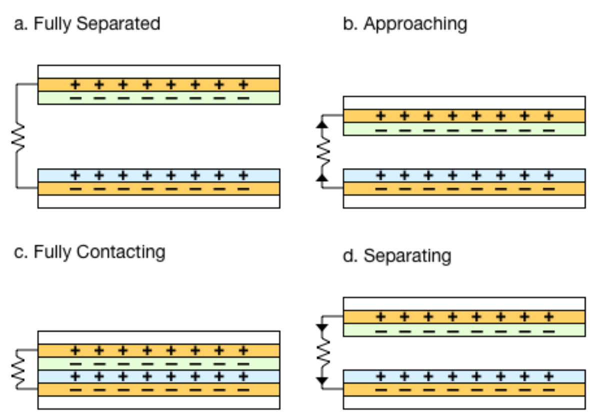

Figure 3. Compressing and expanding layers repeatedly generates triboelectric charges, which can be used to operate connected sensors and actuators.

After compressive force is applied, these layers are brought into contact. Due to the different surface electron affinity of the two layers, the PTFE layer becomes negatively charged, and the nylon layer becomes positively charged. PTFE is suitable as a triboelectrification layer because it is an electret material and its high electron affinity. After the layers are separated, nylon electrostatically induces positive charges on the upper copper tape layer. Conversely, the PTFE electrostatically induces negative charges on the lower copper tape layer. This charge separation produces a potential difference between the two copper layers. Electrons are driven from the upper copper tape layer to the lower copper layer, producing current in the opposite direction. When the PTFE and nylon layers are brought towards contact again, the induced charges on the two copper tape layers decrease, driving the electrons from lower to upper copper tape layers until the PTFE and nylon layers are in full contact with each other again. This illustrates a full cycle of the electricity generation process.

SPIN operates as an alternating circuit (AC) energy generation source. As the two layers approach each other, there is a positive current flowing through the load. As the two layers separate from each other, there is an opposite current flowing through the load. Energy harvested could be utilized in two ways: as instantaneous power or as a stored harvested energy source. Specifically, as an instantaneous power source, the power module could be used as a self-powered sensor, in which generated AC signal is sensed and measured. The voltage spike in AC signal could also be used to drive low-power electronics like LEDs and LCD displays which turn on instantaneously. On the other hand, when storing harvested charges from the power module in an energy storage device, a full-bridge rectifier needs to be connected to the module. This converts the AC signal to DC, with the negative current converted into positive current. The resulting DC signal is used to charge an energy storage device. Once the energy storage device reaches the desired voltage, the accumulated power can power the electronic load.

3.2 Form Module: Crease Patterns

The second building block of SPIN is the form factor of paper creases. The shape, size, and orientation of a crease pattern define not only the aesthetics but also the functionality—the way a paper device responds to both push and pull. Within the form module, we present four different crease patterns (Figure 4): Stripe, Miura, Yoshimura, and Waterbomb folds. While all four afford push-and-pull based interactions, we selected them to compare the relationship between the different levels of complexity in folds and the power generation.

The four patterns provide different strengths and weaknesses in terms of energy harvesting feasibility by nature of their form factors. For example, one pattern may have a greater total contact surface area as a result of its crease pattern, theoretically increasing power generation. But another pattern may actually have greater power generation because it is more easily compressed fully in one hand. Efficient power generation also relies on full pressurized compression across an entire power module. In short, a given module is not just measured according to one factor but a holistic group of elements.

Many factors that affect power generation have been identified [21], but our investigation mainly focused on two: maximum displacement (the maximum distance between two contacting sides) and contact surface area (the total surface area across all power modules on one application). Because of its direct connection to form and structural factors of paper creases, the facet of maximum displacement with which we focused was stiffness. This is how easily a folding pattern fully compresses — and conversely, how easily it goes back to the fully separated form.

Understanding trade-offs became critical in exploring form modules. Here, we describe the unique traits of each crease pattern: Stripe, Miura, Yoshimura, and Waterbomb folds (Figure 4&5 from left).

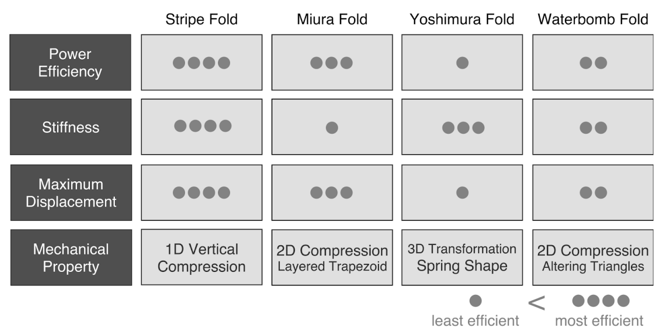

Figure 4. Form module overview.

1) Stripe Fold: 1D Vertical Compression
This was the least intricate folding pattern as it only included vertical subdivisions. This allows for compression and expansion in only one dimension. Its simplicity helps in generating energy and efficiently using space. The Stripe pattern enables the most maximum displacement, which is almost double the separation that the other three folds have. The pattern maximizes contacting area, total surface area of the embedded power modules, and makes it easy to connect circuits across an entire sheet of paper.

2) Miura Fold: 2D Compression with Layered Trapezoid
Miura fold most noticeably has a negative Poisson ratio, meaning it expands and compresses along multiple axes with only one axis of movement. In materials with a positive Poisson ratio like a rubber band, expansion from both left and right will cause the material to compress in the middle. However, pulling the Miura fold from left and right causes the top and bottom to expand out as well, demonstrating this property. The pattern also provides great stiffness, allowing repeated push-and-pull movements.

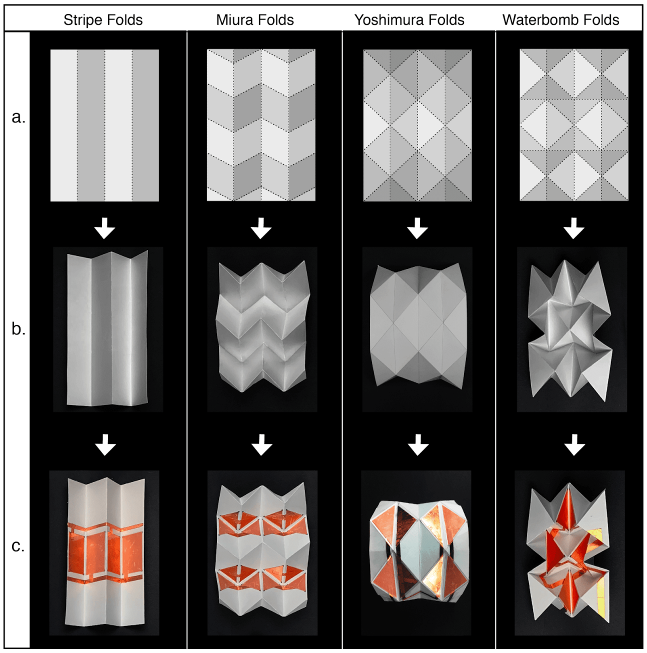

Figure 5. We applied and tested four different crease patterns of the form module and their impacts to the power module efficiency: (a) folding net (b) folded model (c) TENG application.

3) Yoshimura Fold: 3D Transformation in a Spring Shape
Yoshimura fold has many contacting layers which fold into a much smaller and slightly rounded profile. When folded, it creates a spring-like form. While its energy harvesting was not as efficient as other patterns, this three-dimensional form allows exploring different types of potential applications.

4) Waterbomb Fold: 2D Compression with Triangles
Waterbomb fold functions mainly as a base fold. Many folded paper forms employ this as the initial folding pattern before adding more folds to create a new form. While versatile in allowing for the creation of unique forms, it is difficult to apply consistent and full pressure.

Power Generation Measurement
To enhance our understanding about the design trade-offs of all folding patterns regarding the feasibility of power generation, we measured the voltage generation levels of all folding patterns (Figure 4 & 5).

In order to focus solely on the impact of the form factors of the folding patterns, we standardized all other possible elements. We used sheets of 9" x 6" bristol paper across all four crease patterns. Each pattern had the same total contact surface area — 13in² (+/- 0.1 in²) — of embedded power modules, all connected in parallel (Figure 4c). However, we had to use a different amount of power modules depending on the crease pattern.

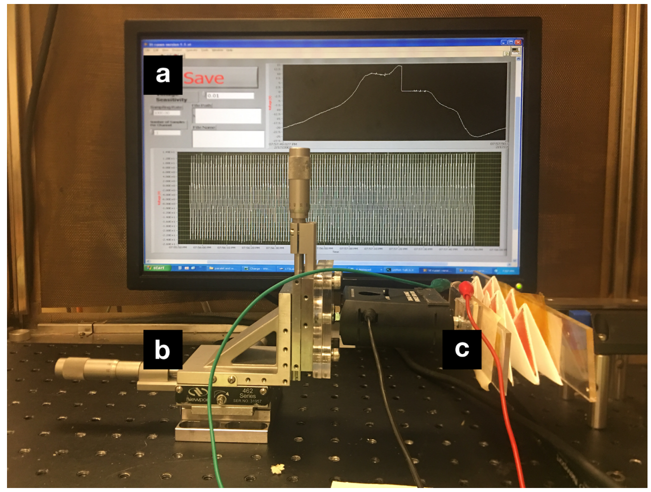

Figure 6. Measurement test setting: (a) computer running software that recording readings; (b) a commercial linear motor that compresses two ends with a specified force, replicating a consistent, repeating fold; (c) a TENG-applied paper crease that we were measuring, in this case the Waterbomb fold.

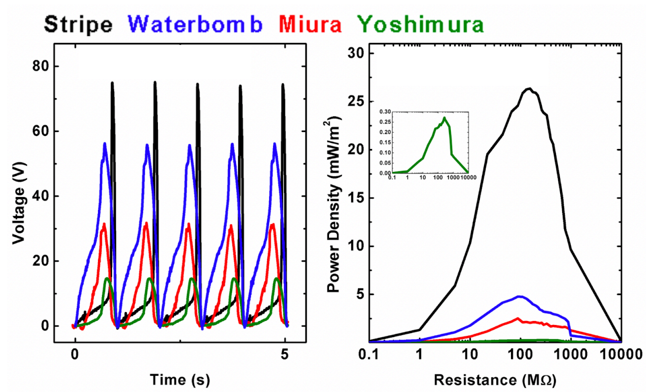

Figure 7. (Left) Open-circuit voltage comparison; (right) power comparison across a period of 15 minutes.

We could only fit 2 units for the Stripe fold, 8 units for the Miura fold, and 4 units for both the Yoshimura and Waterbomb folds. We placed each crease pattern between two ends of a commercial linear motor (Figure 6). The distance between the two ends depended on the stiffness of a given crease pattern — stiffer crease patterns were extended less. The total extension of the Stripe pattern measured 55mm wide, the miura measured 21mm, the Yoshimura measured 28mm, and the Waterbomb measured 27mm.

The measurement showed that the Stripe pattern generated the most open-circuit voltage at 75 volts. Following this, Waterbomb pattern created 55 volts, the Miura fold generated 34 volts, and the Yoshimura generated 14 volts, all shown in Figure 7 (left). Because contact surface area was standardized, the main explanation for the results is the maximum separation distance parameter. The maximum separation between PTFE and nylon layers in each unit are as follows: the Stripe pattern, 22.5 mm.; the Waterbomb pattern, 15 mm.; the Miura pattern, 12.5 mm.; and the Yoshimura pattern, 7.5 mm. Thus, the largest open-circuit voltage would be the Stripe, followed by the Waterbomb, Miura and Yoshimura patterns, which is verified by the experimental results shown in Figure 7 (right).

Furthermore, the power density — the total output power of each pattern normalized by the total contact area — for each folding pattern is also measured at different resistances shown in Figure 7 (right). The power density was defined by the power divided by the contact area between the PTFE and nylon layers. Unlike the open-circuit voltage, which is done at open-circuit, infinite resistance, voltage across different load resistance were measured. The power was calculated by the equation:

$$P = \frac{V^2}{R}$$

The maximum power density for the Stripe pattern is 26.35 mW/m2 at a load resistance of 154 MΩ; for the miura pattern, 2.52 mW/m2 at a load resistance of 88 MΩ; for the Yoshimura pattern, 0.272 mW/m2 at a load resistance of 264 MΩ; for the Waterbomb pattern, 4.768 mW/m2 at a load resistance of 88MΩ. The power density measurement shown in Figure 7 was further used in the design editor to estimate how much power the selected form modules could generate.

3.3 Function Module: Sensors and Actuators

The last building block defines interaction behaviors. We can develop SPIN for both sensing and actuating purposes.

In terms of sensing, for instance, SPIN fits well in sensing touch and the force behind an interaction. Electric signal generated from a user interacting with SPIN can measure pressure; greater force applied by a user creates a higher voltage peak compared to a low force input.

For actuation, SPIN can power actuators LEDs, e-paper displays, and buzzers. For the former two instantaneous applications such as lighting up LEDs or e-paper displays, no additional parts are necessary. For the latter application that uses stored energy, a rectifier is required to convert the output AC signal into DC signal. In addition, whereas the rectified signal is high voltage (approximately ~20V), the electronic devices that we attempt to power usually require a low voltage (approximately 1.5-6 V). Thus, the rectified signal needs to be stored in a capacitor. Once the capacitor reaches the desired voltage, the system will power the electronic device.

4. SPIN DESIGN EDITOR

Making paper creases can be challenging as it requires calculation, modeling, and hand-skills. Particularly, in SPIN design, we needed to determine the positions of self-power modules. In order to embed them, we had to prepare separate digital files to cut different materials while calculating power generation based on the surface area of the embedded power module and crease patterns. In order to assist the SPIN design and fabrication, we developed design software. The editor supports users by following five steps: (1) Folding type selection from a folding pattern library; (2) Adjusting parameters to develop their own design; (3) Selecting TENG unit positions; (4) Estimating power generation; (5) Exporting three different files for paper crease, copper adhesive layers, and PTFE/nylon layers.

Step 1: Folding Type Selection
Our design software allows users to select a folding pattern to start creating a paper interface design. Currently, the four patterns we investigated are provided: Stripe, Miura, Yoshimura, and Waterbomb folds (Figure 4).

Step 2: Parameter Adjustment
Starting from the selected folding pattern, users can adjust the local parameters (such as the number of rows and columns or the width and height of each crease unit) on the right panel (Figure 8a). Depending on the folding patterns, the parameter sets can vary. For example, the Stripe folding pattern features no rows. As a result, it only has the number of unit columns with width and height of each unit. The Miura pattern, however, can vary depending on the angle of each unit. Therefore, it has parameters adjusting the number of both rows and columns, width and height, and "slope" of each unit (Figure 8b).

Step 3: TENG Unit Selection
After finalizing their crease design, users can select where to apply the self-power modules. Given the nature of the embedded technology – how TENG requires two surfaces to contact each other in order to generate power – selecting one power module includes a pair of crease units. Figure 8c shows that each color line represents different materials (blue and green for PTFE and nylon sheets; yellow for copper adhesive sheet).

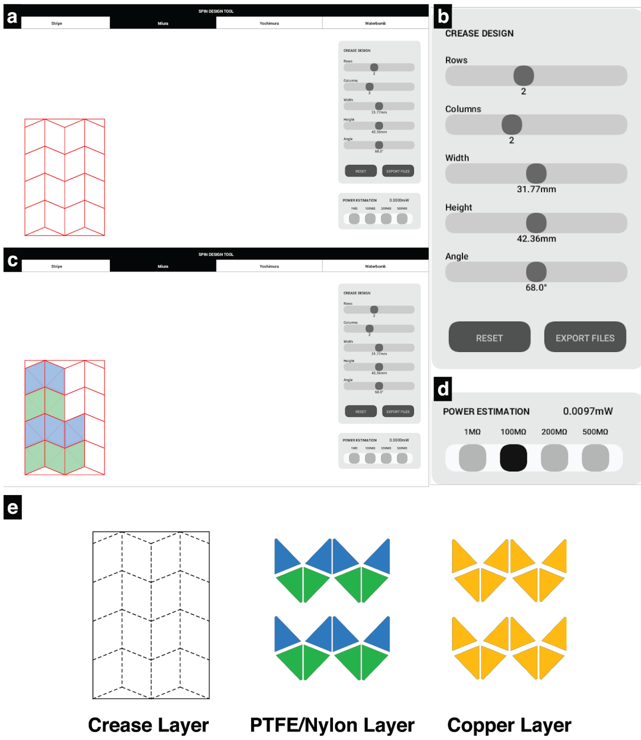

Figure 8. SPIN design editor walkthrough: (a) Select a folding type and adjust parameters; (b) Crease Design palate to adjust parameters (from the top: Rows, Columns, Width, Height, Angle and two buttons for "Reset" and "Export Files"); (c) Select where to apply the self-power modules; (d) Estimate generated power by selecting a resistor; (e) Export files for paper, copper, and PTFE layers of the final design.

Step 4: Power Estimation

Based on the maximum power density that we gained from Figure 7, we simulated how much power the SPIN unit that a user creates can generate. While configuring the power module embedment, users can estimate how much power the selected modules can generate as shown in Figure 8d. The level of power generation is calculated based on the total surface area of selected power modules and its load resistance as follows:

$$P = P_n \times A$$

Where total generated power is P, power generated per unit area depending on load resistance is P_n, and total surface area is A.

Moreover, embedding the exact same power modules can generate different amount of electric power based on the load resistance connected. The editor supports this by calculating the power generation and changes accordingly depending on the selected load resistance option.

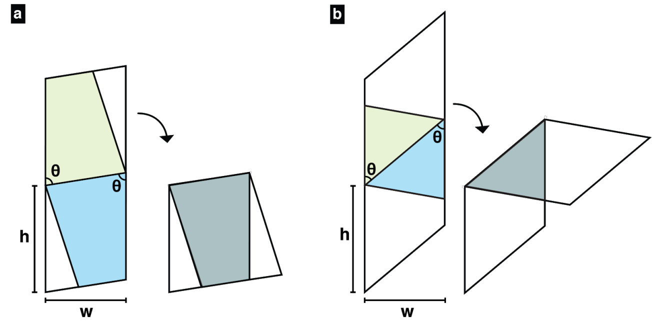

Figure 9. Each Miura folding pattern unit's overlapping part shape changes depending on the unit corner's angle: (a) trapezoid contact area, and (b) triangle contact area.

The amount of contact surface area is a critical part of the power estimation since the amount of the generated power depends on the total embedded power module surface area. For Stripe, Yoshimura, and Waterbomb patterns, the power module surfaces of each pair contact the other side's full surface area. However, for the Miura pattern, the embedded-power module surfaces of each pair only contact a part of the other as shown in Figure 9: (a) Trapezoid contact area (b) Triangle contact area. In particular, the partial contact area shape changes depending on the unit corner's angle (θ) as follows:

$$\textbf{(a)} \quad \frac{w}{\sin(2\pi - 2\theta)} \geq h$$

$$\textbf{(b)} \quad \frac{w}{\sin(2\pi - 2\theta)} < h$$

As long as the condition above, depending on whether the miura fold features a trapezoidal or triangle shape, is satisfied the corresponding equations below can be used to calculate the total contacting area.

$$\textbf{(a)} \quad wh - h^2 \sin\theta \cos\theta$$

$$\textbf{(b)} \quad \tfrac{1}{2}w \times \frac{w}{\sin(2\pi - 2\theta)}$$

By following this principle, the software estimates the amount of generated power of the final SPIN design.

Step 5: Export Files for Fabrication

After finalizing a SPIN design, users can download SVG files by pressing "Export Files". The software generates three vector files for paper crease, copper adhesive, and PTFE/nylon layers separately.

5. SPIN FABRICATION TECHNIQUES

Figure 10 shows a walkthrough of the fabrication based on five steps: (1) Using the file generated from the SPIN editor, prepare all materials (paper, copper adhesive, PTFE sheets) by cutting and scoring; (2) Fold and crease paper; (3) Attach copper adhesive layers to the self-power module positions;

(4) Attach PTFE layer on one side of the power modules; (5) Test to ensure the stable connection across the power modules.

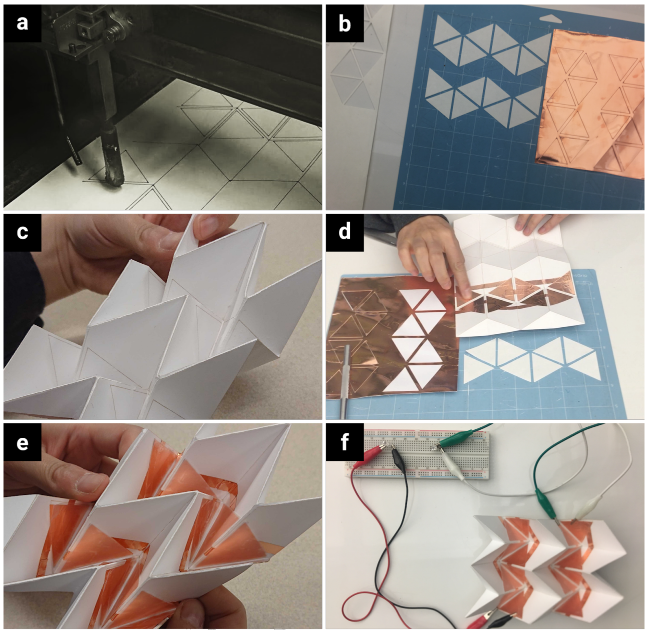

Figure 10. SPIN fabrication step-by-step workflow.

Step 1: Cutting and Scoring Materials
Using the digital files generated by the system, users can cut and score materials. Any digital cutting machines such as a laser cutter or vinyl cutter can support this stage. That said, material considerations, especially copper (and optionally, nylon), may affect which cutters are viable. For our fabrication, we preferred vinyl cutters based on the variety of materials that it can work with – however, the bed size or finding the proper cutting blade often caused a problem.

Step 2: Folding and Creasing Paper
In order to accommodate folding and creasing paper, it is important to score the paper in the previous step. It greatly expedites the process, eliminating the tensions for accuracy, especially in patterns like the Miura fold in which the angles of each crease impact the contact surface area of embedded power modules.

Step 3: Attaching Copper Adhesives
Once folded, users need to attach the copper adhesives for all power modules and connect them. In our pre-material exploration, we tested applying other conductive materials such as inkjet printing with silver ink on paper and conductive painting. However, all except for the copper tape option were broken when repeatedly folded. As a result of SPIN being based on contact electrification via a crease mechanism, copper tape best affords our purpose. We highly recommend using double-sided copper tape (conductive on both sides) for connections across power modules.

Step 4: Attaching PTFE Sheet
Users then apply the PTFE layer directly over one side of a power module, right over the copper adhesive. In this stage, applying a nylon layer on the opposite side of each power module can greatly increase the energy harvesting efficiency. This will result in a single TENG power module having one side with a PTFE layer on top and the opposing side with a nylon layer as shown in Figure 2. TENG modules connected in parallel must have the side with a PTFE layer connected to the PTFE layer sides of successive TENG modules. In other words, all PTFE sides across power modules are connected to each other, while the opposing side of power modules must be connected in their own circuit.

Step 5: Testing the embedded power module connections
Finally, to ensure if the embedded power modules are well connected and if the form modules successfully afford push-and-pull based actions to generate power, users can use a multimeter. Note that intermittent testing throughout the fabrication process, even before applying layers over the copper type, can lower the risks.

Applications	Self-Power Module	Form Module	Functional Module
Finger Puppet by Pinching	Instantaneous Power	Stripe Fold	IR Transmitter
Voting Counter by Tapping	Instantaneous Power	Yoshimura Fold	Touch Sensor
Accordion Music Box by Stretching	Accumulative Power	Stripe & Waterbomb Folds	Sound Buzzer
Wing Costume by Flapping	Instantaneous Power	Miura Fold	LEDs

Figure 11. Application overview: we developed four prototypes based on different configurations of three building blocks: power, form and function modules.

6. APPLICATIONS

To demonstrate the broad possibilities of the SPIN editor and fabrication techniques, we built four application examples assembling different sets of SPIN building blocks (power, form, and function). All applications are based on repetitive push-and-pull motions as the primary human interaction to activate the self-power modules (Figure 11). We started from exploring SPIN applicable embodied interactions, developing a chart that shows the landscape of the push-and-pull based embodied interactions (Figure 12). We elicited the list of actions throughout "bodystorming [5,8]"–actively investigating our actions by physicallysituated brainstorming, divided them based on the primary body in its physical scale, and adapted four embodied interactions that ranged from a pinching motion with fingers to flapping motion with both arms.

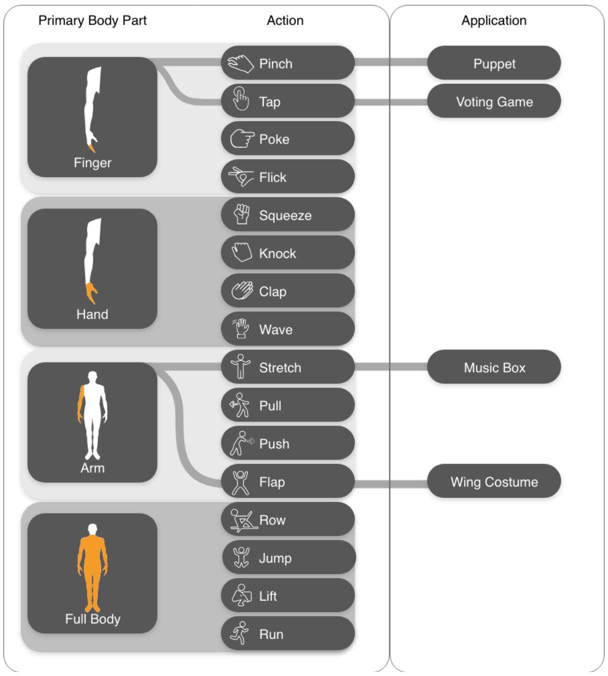

Figure 12. SPIN applicable embodied interactions from a finger to a full-body movement scale.

6.1 Finger Puppet

The finger puppet is created by combining the Stripe folds with an IR transmitter. In order to accommodate a finger-based pinching motion, we used a Stripe pattern that provides the highest maximum displacement, and an IR transmitter is attached directly to the embedded self-power module within the puppet. One pair of the power module is applied to the Stripe fold that is adjusted to fit between one's thumb and index finger. When the dinosaur puppet closes its mouth, the IR transmitter will briefly flash and be sensed by a sensor attached to an Arduino microprocessor [2] located nearby. We developed a fire shooting graphic in Processing [26] that is generated in response to IR light being sensed.

6.2 Voting Counter

We developed a voting counter applying the Yoshimura fold as a button to simulate force and touch sensing. This application adapts the nature of the Yoshimura fold that provides a spring-like property when folded into a playful button for a user to press and embraces it as a part of the graphic design. In this application, by tapping the "vote button" associated with the item, users generate a voltage that can be sensed by a microprocessor. Then, the microprocessor powered by an external power source will light an LED strip that will be displayed back to the user on the item they tapped on.

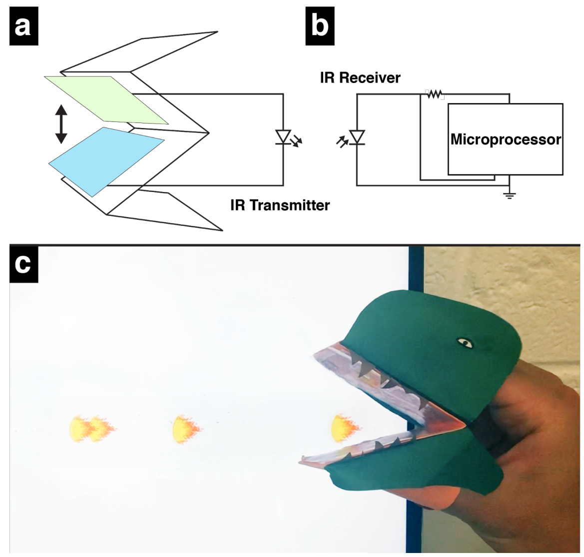

Figure 13. (a) connecting an IR transmitter with a Stripe fold; (b) embedded schematic; (c) as the dinosaur puppet opens and closes its mouth, the screen behind connected to the IR receiver generates shooting fire graphics.

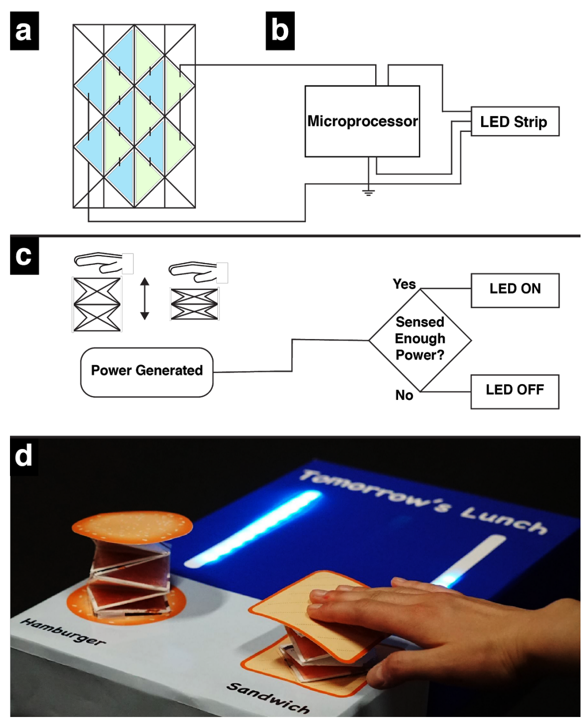

Figure 14. (a) applying the Yoshimura fold as a vote button; (b) embedded schematic; (c) logic flowchart for the SPIN sensing technique; (d) as the buttons are pressed, they send a voltage peak to the connected microprocessor, which then lights up LED strips.

6.3 Accordion Music Box

Our music box is designed with the combination of the Stripe and the Waterbomb folds. It powers a sound buzzer to play a melody as we repeat compress and expand the device, representing the scene of "playing an accordion". We used the Stripe fold to apply the self-power modules with high power efficiency and adapt the Waterbomb fold as a geometric bridge to connect two different dimensions of the Stripe folds. This combination allowed the Stripe pattern to wrap around itself, making a more condensed pattern that also fits within the elastic aesthetics of an accordion. To operate the embedded melody generator circuit, this music box requires a high amount of DC current, so in our application, the embedded power modules are attached to a rectifier and a 10k uF capacitor. As a user "plays" the accordion, the capacitor will receive a small amount of charge. After a substantial amount of compression and expansion, the capacitor will discharge into the melody generator circuit briefly, creating a sound.

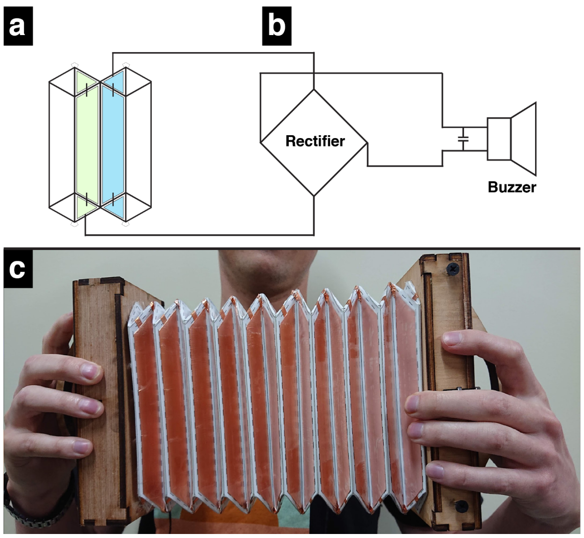

Figure 15. (a) a combined form of a Stripe and Waterbomb folds connected to a melody generator circuit; (b) embedded schematic; (c) as the accordion-looking device is compressed and expanded, it charges electricity and play a melody.

6.4 Light-Up Wing Costume

Applying a flapping motion, we developed a larger scale application. This light-up wing is an interactive costume that users can wear by attaching it to their arms and torso. By flapping their arms, a user can light up the LEDs integrated into the costume. We adapted a Miura pattern as it deploys flexible 2D-based compression and expansion that suits for our embodied interaction in a large body scale. As shown in Figure 16, the embedded power modules are divided into separate sections, with each section independently powering the LEDs that are attached. This allows more robustness in the circuit overall, while also creating a more dynamic lighting effect of the LEDs from slight variations in the power generated.

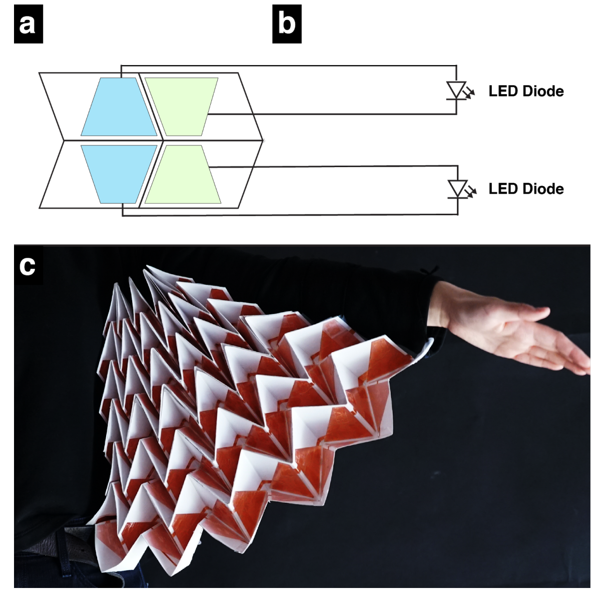

Figure 16. (a) integrating LEDs with Miura folds; (b) embedded schematic; (c) while flapping the wing, it lights up the LEDs.

7. LIMITATIONS & FUTURE WORK

The SPIN still has several challenges in achieving the maximum energy harvesting efficiency, finding a right functional module, and designing with spatial mapping. These limitations also inspire us to discuss future work.

First, inconsistency in mechanical strength limits the energy harvesting efficiency. It's hard to ensure whether the two facing surfaces of a power module are meeting or leaving at the same time and whether the same compression or expansion strength applied to multiple power modules. As inconsistent compressions as well as inconsistent contacts cause energy loss, consistent, full contacts of power modules are required to maximize the energy harvesting. However, when it comes to embodied interactions, human body doesn't afford such consistent and steady movements, so while exploring application examples, we learned that it's impossible to expect the maximum power efficiency that was measured in a lab facility. We consider this an inherent condition from integrating thin and flexible materials such as paper as a medium with TENG for self-powered interfaces.

Second, although our design editor currently supports power estimation, prior knowledge on electronics including finding a right functional part is still required. Our self-power module is based on TENG, which is a high impedance device, while many electronic devices are low in impedance. Accordingly, some functional modules are better suited for the SPIN applications. For instance, LCD displays and IR wireless communications are low in impedance and can benefit more from SPIN. We plan to improve the scope of support for building circuits in the SPIN editor by providing a guidance to find proper parts.

Lastly, different crease patterns provide different challenges as well as opportunities for both expressive and technical aspects. Folding paper requires spatial mapping and it is quite challenging for many designers, especially when it comes to combining with additional structures (such as TENG). In our experiment (see Section 3.2), we learned by exploring with our hands and spending a large amount of time and effort, and this would prevent inviting more designers to explore SPIN possibilities. To address this, we will consider adding a feature of 3D rendering view in the design software to help users understand the relationship across the crease patterns, folding motions and energy harvest efficiency.

8. CONCLUSION

We developed a set of fabrication techniques and a design editor to create self-powered paper interfaces adapting TENG technology. Integrating folding paper creases with triboelectric nanogenerator, we used repetitive push-and-pull based embodied movements as a power source. Our examination began with a material-driven exploration of paper folding, a thorough understanding of triboelectric nanogenerators and their integrated potential to adapt paper folding for self-powered interfaces. Investigating different crease patterns and their energy harvesting feasibility, we learned the importance of the maximum displacement factor and adapted the measurement into the development of our design software to provide the estimation of power generation based on the selected crease patterns. Throughout this study, we envision a future paper-based interface that fully incorporates a power source as well as sensors and actuators while presenting the rich materiality of paper, and this paper presents some of the possibilities.

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