Paper Generators: Harvesting Energy from Touching, Rubbing and Sliding

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ABSTRACT

We present a new energy harvesting technology that generates electrical energy from a user's interactions with paper-like materials. The energy harvesters are flexible, light, and inexpensive, and they utilize a user's gestures such as tapping, touching, rubbing and sliding to generate electrical energy. The harvested energy is then used to actuate LEDs, e-paper displays and various other devices to create novel interactive applications, such as enhancing books and other printed media with interactivity.

Author Keywords: Energy harvesting, touch, gestures, tangible computing, paper electronics, interactive books.

ACM Classification Keywords

H.5.m. Information interfaces and presentation: User Interfaces-Graphical user interfaces; Input devices & strategies.

General Terms: Human Factors; Design; Measurements.

INTRODUCTION

This paper presents the design and exploration of a new energy generation technology that harvests electrical energy from touching, tapping and rubbing gestures applied by users to thin, flexible, paper-like structures. These gestures actuate LEDs, e-paper displays, buzzers and IR transmitters. The energy harvesting structures are assembled from inexpensive everyday materials such as common paper and Teflon® sheets; they are flexible, light and durable. Our energy harvesting technology can be easily embedded into everyday objects, such as printed books, postcards and board games, enhancing them with rich interactivity without requiring batteries or external power sources (Figure 1).

The Paper Generators presented in this paper are based on *electrets* that have been exploited for decades in designing sensors and MEMS-based energy harvesting devices [17]. We demonstrate that electret-based energy harvesting can be effective at the macro scale when human gestures are carefully matched to the design of structures producing

Figure 1. Paper Generator harvests energy from rubbing and activates the e-paper display, revealing the word "hello".

electrical power. Developing, exploring and evaluating interactive power generators based on electrets are some of the major contributions of this paper.

It is important to highlight the differences between our approach and power harvesting/scavenging technologies popular today. Traditional power harvesting techniques often focus on *incidental* collection of "wasted" energy, such as the electromagnetic radiation around cell towers, ambient vibrations, or even the motion of a beating human heart [13, 20]. In this work, we explore *explicit* power generation where users actively generate power to achieve desired results [14]. In this respect our work follows the tradition of hand-wound radios and human-powered interaction devices such as Peppermill [18] and InGen [4] among others.

There are multiple applications of our power generating devices. In this paper we explore applications in designing interactive self-powered printed books where the reading experience is enhanced with simple interactivity that is either happening *locally* on the book itself or *remotely*, by triggering external computing devices. Augmenting paper books, notebooks and other paper products with computer-driven interactivity has been a burgeoning area of research and development [8, 3, 15]. In particular, we were inspired by such work as Electronic Popables [15] where traditional pop-up books were instrumented with a range of sensors, light sources and actuators to enhance reader experience.

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Although exciting and enjoyable, the need for electrical power limits the feasibility of interactive books by increasing their cost, weight, and size, and by decreasing their shelf life. Developing a basic set of interactive elements that allow for the design and development of self-powered interactive books is another contribution of this paper.

In the rest of the paper we present the principles, design, implementation, application and evaluation of our technology. The main contributions of this work are as follows:

1. We propose a novel energy harvesting technology based on electrets that allows harvesting energy from a variety of human gestures such as touching, tapping and rubbing. The energy harvesting structures are made from thin, flexible commonly available paper-like materials.

2. We design a set of energy harvesting structures and matching gestures that can effectively generate electrical power. We call them Paper Generators, and they form the building blocks that allow for the design of self-powered interactive devices, such as paper books, posters and cards.

3. We implement a number of interactive self-powered scenarios in printed form that demonstrate the use of Paper Generators for actuating interactive devices, such as LEDs, e-paper displays, IR transmitters and rotating needles.

RELATED WORK

Generating power from human motion requires designing devices that convert the motion of the human body into other forms of energy. Some of the earliest convertors were designed, perhaps, during the early Stone Age when humans learned to produce fire by rubbing two pieces of wood together. Modern convertors or *power generators* focus on the generation of electrical power from a wide range of human activities, such as walking, running, riding a bicycle, or moving various mechanical devices [13, 9].

Often there is a distinction made between passive and active energy generation [14]. In the case of passive harvesting, the energy is collected in the background, then blended into everyday human activities, such as walking or breathing [16]. These devices are often designed to be undetectable to the user wearing them; they do not require conscious attention or learning how to use them.

In the case of active energy harvesting, the human has to consciously perform actions leading to the creation of electrical power that can either be stored or used immediately [4, 18]. One of the earliest known devices designed to produce electrical power from human motion was the survival radio developed during WW2 [10]. Today, there is a wide variety of hand-cranked electrical devices such as flashlights and radios. Furthermore, a number of research projects have explored the use of the human power generation in various interaction devices, such as remote controls [4, 18]. In this paper we are following the same direction by focusing on active harvesting of electrical power from human activities.

The central element in any energy generation device is the *generator*, a device that converts one form of energy into another. Numerous generators for human power generation have been explored, such as piezo-based devices that produce power from pressure and vibration, electrostatic vibration generators, thermal convertors, magnetic induction-based generators and RF-based electrical generators [7, 9, 11, 13, 20]. The underlying principle of electrical power generation defines the efficiency of generation and the type of required human actions, e.g., piezo generators might have to be shaken, while a magnetic induction-based generator might require the user to turn a crank. Designing power harvesting and generation devices, therefore, has to be considered from the user interaction perspective because different interaction activities require quite different power generators. In this sense, we can consider human power generation a user interface design problem.

In this paper we propose a novel method of human-based electrical power generation by moving two electrodes with induced charge relative to each other. The physical principles behind electret design have been known for a long time and used in developing sensors, such as microphones, as well as MEMS-based harvesters that convert ambient vibration into electrical power [17]. Recently the electret principle was utilized to convert human finger tapping into power to actuate an array of flashing LEDs [19], an important first step in exploring this power harvesting approach at the macro scale. The reported devices, however, required complex and expensive microfabricated structures, i.e., silver coated nanowires deposited on a plastic substrate. The energy harvester presented in this current paper differs from [19] in structure and function and uses common materials that do not require microfabrication. While only a single mode of operation was investigated in [19], we demonstrate a variety of structures that allow for the use of different gestures and interactions in a broad variety of applications.

PRINCIPLE OF OPERATION

Energy harvesting devices typically employ a magnetic or electric field source, such as a small battery, a permanent magnet, or a permanent electret [12]. In our application, the field source is the semi-permanent charge on the surface of a thin and flexible sheet of PTFE (polytetrafluoroethylene), commonly known by its brand name – Teflon. When the sheet is rubbed with ordinary newspaper, opposite-polarity charges σ_P and σ_T accumulate on the surfaces of the paper and PTFE due to the triboelectric effect (Figure 2a). Because PTFE has a lower electron affinity than paper, charge σ_T is negative [2]. This charge on the PTFE sheet can then act as an electric field source.

When the PTFE sheet is brought near conductive objects, e.g., sheets of aluminum (Figure 2b), the charge on the PTFE attracts free charges of opposite polarity σ_1 and σ_2 that are available in the conductors. These charges accumulate on the surface of the conductors, as shown in Figure 2b.

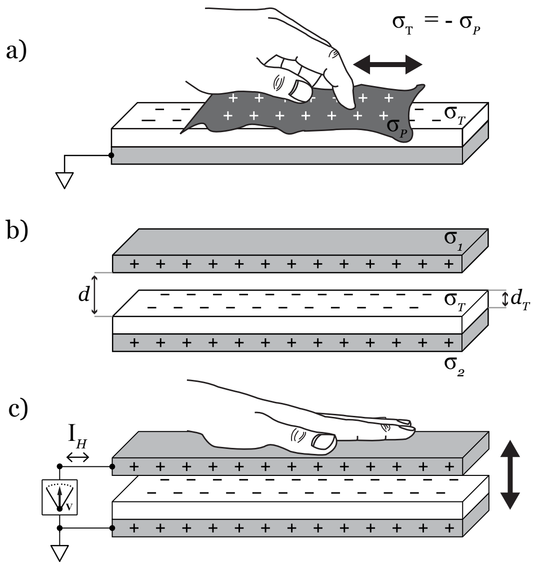

Figure 2. Principle of operation: a) The PTFE sheet is charged by rubbing it with newspaper; b) opposite polarity free charge is induced on the surface of electrodes; c) when the electrodes move relative to each other, a potential difference is created.

The operation of the Paper Generators relies on the *movement* of the two conductive sheets relative to each other and the electric field source, i.e., PTFE. As the relative positions of the sheets change, the distribution of the induced charges, the electric field, and the total capacitance between the sheets change, resulting in an electric potential difference between the conductors (Figure 2c). Hence, the mechanical movements of the sheets and the field source are converted into electrical potential energy that can do work.

It is important to emphasize that although the fundamental principles of operation are relatively simple, a broad variety of movements and gestures can be used to generate power by designing structures that are highly optimized for specific gestures. Different materials for electrodes and electret can also be used. In the next section we analyze the most basic structure shown on Figure 2.

Paper Generator Model

The structure of the Paper Generator that we used for analysis is as follows: a 50 μm, 14-by-8 cm PTFE sheet is stacked on top of a 127 μm thick sheet of silver-coated polyester (henceforth "electrode") with its silver-coated side facing the PTFE. A second electrode is placed above, with its silver-coated side facing the PTFE. The top electrode is supported by a 5 mm thick piece of flexible foam rubber on the sides, which separates it from the bottom PTFE-electrode stack by a gap of approximately 5 mm and allows for the deformation of the top electrode in the center. The top surface of the electrode is covered with common paper, providing stiffness to the top electrode. The whole structure is then attached to a large sheet of paper. All sheets are attached to each other and to the page using common adhesive tape. Wires are attached to the electrodes using silver-filled conductive epoxy (MG Chemicals 8331) to provide electrical connection. Figure 3a shows the energy harvester, with the top electrode opened, revealing the construction. Figure 3b shows the generated signal on the oscilloscope screen as the user brings the electrodes into contact with each other by pressing on the top electrode.

Analysis

We analyze the operation of the energy harvester in two modes by investigating both *short circuit current* and *open circuit voltage*. These give us upper bounds for the current and voltage that can be supplied by the Paper Generators as a power source. For simplicity, we assume that initially both electrodes are connected to a common ground (Figure 2c). Therefore, any excess negative charge is discharged to the ground, leaving a net positive charge on the electrodes to counter the electric field created by the charged PTFE.

Short Circuit Current

When the two electrodes are connected to each other through a small resistance, they are at the same potential at the steady state (Figure 2b). Because the electric field inside the conductors is zero at the steady state, the charge density in equilibrium on the bottom sheet, σ_1, the top sheet, σ_2 and the PTFE, σ_T, are related to each other as:

$$\sigma_1 + \sigma_T + \sigma_2 = 0 \ , \qquad (1)$$

indicating that the total charge on the electrodes is equal but opposite in polarity of the total charge σ_T. In (1), the bound charges due to polarization of the dielectric (PTFE) are omitted, as their net effect is null. The potential difference, V, between the electrodes can be found by the line integration of the electric field between them [18]. It will be zero because the electrodes are shorted:

$$V = \int_0^{d_T+d} \vec{E}\cdot \mathrm{d}l = \frac{\sigma_1}{2\varepsilon_0}\left(\frac{d_T}{\varepsilon_T}+d\right) - \frac{\sigma_2}{2\varepsilon_0}\left(\frac{d_T}{\varepsilon_T}+d\right) + \frac{\sigma_T}{2\varepsilon_0}\left(-\frac{d_T}{\varepsilon_T}+d\right) = 0, \qquad (2)$$

where ε_T is the relative dielectric permittivity of PTFE (≈2, [7]), d_T is the thickness of the PTFE sheet, d is the distance between the PTFE and the top electrode, and ε_0 is the dielectric permittivity of free space (Figure 2b). Defining the electrical thickness of PTFE as $d_{TE} = d_T / \varepsilon_T$ and combining (1) and (2) we get:

$$\sigma_1 = -\sigma_T \frac{1}{1 + d_{TE}/d}, \text{ and } \sigma_2 = -\sigma_T \frac{1}{1 + d/d_{TE}}. \qquad (3)$$

Therefore, the charge on the top and bottom electrodes is dictated by the distance, *d;* and by changing it mechanically, induced charges can be moved between the sheets (Fig-

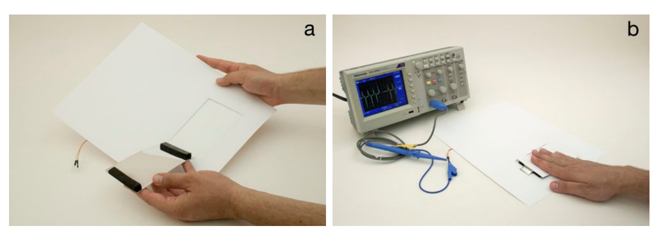

Figure 3. a) The Paper Generator. b) A signal is generated when the electrodes come into contact with each other.

ure 2c). If an electrical load, such as a resistor or an LED, is connected between the two electrodes, the current flowing through the load *will do electrical work*.

Let's assume that the initial and final distances between the electrodes are d_i and d_f, their surface areas are A, and they move for Δt seconds. The average harvested current, $I_{H,}$ flowing from the top electrode to the bottom electrode can be calculated as:

$$I_H = \frac{\Delta Q}{\Delta t} = \frac{A(\sigma_1^f - \sigma_1^i)}{\Delta t} = \frac{A\sigma_T}{\Delta t}\left(\frac{d_i}{d_i + d_{TE}} - \frac{d_f}{d_f + d_{TE}}\right). \quad (4)$$

Equations (3) and (4) suggest that when the top electrode is brought closer to the PTFE, ($d_f < d_i$), the current is negative; flowing from the bottom electrode to the top. When the top electrode is moved further away, ($d_f > d_i$), the current is positive and flows in the opposite direction. When the top electrode is brought into contact with PTFE, ($d_f = 0$), the total charge flowing out of the top electrode increases with the PTFE surface charge density, the electrode surface area, and the initial distance. The average current also depends on the speed of the electrode movement, i.e., the faster the electrode movement and the smaller the Δt, the larger the current spike.

Open Circuit Voltage

When the electrodes are not connected to a load, their potential difference is free to change with distance d. Assuming that the initial and final distances between the sheets are d_i and d_f respectively, and the initial potential difference is zero, the potential difference at the final state is:

$$V_f = \int_0^{d_T + d_f} \vec{E} \cdot \mathrm{d}l = \frac{\sigma_2 - \sigma_1}{2\varepsilon_0}\left(d_{TE} + d_f\right) - \frac{\sigma_T}{2\varepsilon_0}\left(d_{TE} - d_f\right). \quad (5)$$

Combining (5) and (3) we get:

$$V_f = \frac{\sigma_T}{\varepsilon_0} \cdot \frac{d_{TE}(d_i - d_f)}{d_i + d_{TE}}. \quad (6)$$

Therefore, for the case where $d_f = 0$, i.e., when the top plate moves down to make contact with the PTFE, the voltage between the plates reaches:

$$V_f = \frac{\sigma_T}{\varepsilon_0} \cdot \frac{d_{TE} d_i}{(d_i + d_{TE})}. \quad (7)$$

Because σ_T is negative, the contact voltage is also negative. According to (6), the voltage approaches infinity as the top sheet is moved farther away ($d_f \rightarrow \infty$), which is impracticable. This is because the analysis presented is based on a parallel plate capacitor model, which assumes that there are no fringing fields outside the capacitor. In reality, with the increase of distance, d, the parallel electrode plates behave like point charges, and the electric fields dissipate with the distance. Therefore, the analysis presented here is valid for separation distances that are smaller than or comparable to the side length of the electrodes.

Measurements

We measured the *short circuit current* by connecting a small resistor between the two electrodes, and the voltage drop across the resistor was measured using a Tektronix P2220 voltage probe (10 MΩ, 16 pF). Because the short circuit current is on the order of hundreds of microamperes, a 1 kΩ load provided enough voltage drop to be separated from noise while still being approximated as zero volts.

Figure 4a demonstrates the current spikes measured from three separate "taps" using the test energy harvesting apparatus described above. Each tap consists of a large negative current spike reaching up to −500 μA lasting 1-4 ms. When the user's hand is lifted approximately 100 ms after initial contact, a positive current flows, restoring the original charge distribution as the plates return to their initial position. The speed of recoil depends on the spring constant and elasticity of the foam rubber and the top sheet. The typical recoil current peak is a lot smaller (≈ 30 μA) lasting up to 50 ms, allowing for a total charge of ≈ 400 nC to flow back.

The *open circuit voltage* of the energy harvester was measured using a Tektronix P5122 high voltage probe (100 MΩ, 4 pF). The voltage between the two electrodes was measured relative to the bottom sheet while the user taps the top sheet, bringing the two into contact. It results in a sharp negative voltage drop followed by a positive spike during recoil as seen on Figure 4b. The negative drop dissipates because once the contact between top and bottom sheets is established, the voltage diminishes due to the finite input resistance of the probe. This allows for a new charge distribution to be established. Similarly, a positive voltage spike occurs as the top sheet recoils. The negative voltage spikes routinely reach −600 V, and recoil voltage spikes can go up to 1200 V, especially when a new charge distribution is achieved with a long pause between contact and recoil.

We measured the power output of the Paper Generators under varying resistive loads, from 1 KΩ to 10 MΩ. Load resistances were connected at the output of the paper gener-

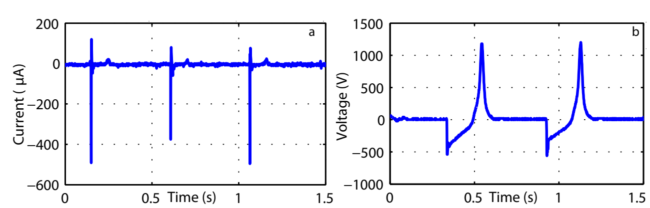

Figure 4. a) The short circuit current of three taps; b) The open circuit voltage during two taps.

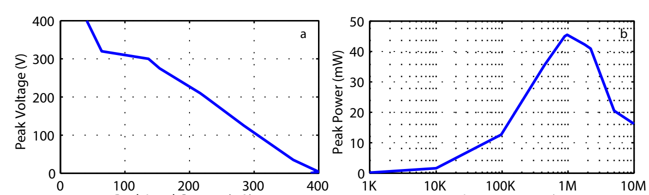

Figure 5. a) VI load line of the Paper Generator; b) Peak delivered power versus load resistance.

Peak short circuit current	−500 µA
Peak open circuit voltage	−600 V
Output resistance R_{out}	1.08 MΩ
Peak voltage at R_{load} =1 MΩ	−210 V
Peak current at R_{load} = 1 MΩ	−210 µA
Total charge moved (short circuit), C	400 nC
Electrical work per tap, R_{load} =1 MΩ, E_c	60 µJ
Average peak power, R_{load} = 1 MΩ	44 mW

Table 1. Summary of measurements

ators and the voltages spikes across them at contact were measured. The values were corrected for oscilloscope probe loading. To minimize the effects of variability between taps, peak values of multiple taps were measured and averaged. Figure 5a plots the peak (negative) voltage of varying load resistors versus peak currents calculated using Ohm's law. The output resistance can be calculated by fitting a line to the curve on Figure 5a which gives us R_{out} = 1.08 MΩ. This is not strictly a Thévenin equivalent resistance, because the voltage and current characteristics of the generator are dynamic and depend on multiple parameters, including tapping speed and contact area. Nevertheless, it can be considered an output resistance for design purposes.

Figure 5b plots the peak power delivered versus load resistances, including probe loading. The maximum peak power is delivered at ≈ 1 MΩ, consistent with the observation from the load line characteristics. Because the peak and average delivered power depend on the square of the current, the total electrical work done per tap, which includes contact and recoil, depends on the speed of the tap. Although the total charge that moves from one electrode to the other at each tap is constant, a faster tap creates higher currents, producing more electrical work even though the current has a shorter duration. Table 1 summarizes the electrical properties of the paper generator that we measured in this section. In addition to peak voltage, current and power, the total electrical work per tap was measured. At tens of microjoules, the electrical work per tap is up to one hundred million times smaller than the energy content of a AA battery. The measurement results presented in Table 1 are taken from a particular user's gestures and vary with speed and contact force. While the application of these gestures is not precise, these measurements establish the output characteristics of paper generators within an order of magnitude.

PAPER GENERATORS

In the previous section, we described a novel energy harvesting technology based on the electret principle; in this section, we demonstrate how this technology can be effectively used to design human-powered, interactive systems.

The principles of power generation that we discussed are simple, and yet they allow for the design of a surprisingly large variety of energy generating structures that permit the use of many different human gestures. A comprehensive investigation of all possible structures is beyond the scope of this paper. Here we discuss some of the most basic designs and illustrate how they can be used to produce more complex power generating structures (Figure 6).

An interactive system based on our energy harvesting technology includes the following three components: 1) *Paper Generators*, energy generating structures made of paper and producing electrical energy from human gestures, 2) *Harvesting Circuits*, electrical circuits that regulate energy produced by Paper Generators, and 3) *Application Components* that use electrical energy produced by Paper Generators.

Materials

Materials that can be used to build Paper Generators are common and inexpensive. A *substrate* is used as a foundation of the design and can be any electrically-proper material, such as paper, PET films, fabric, plastic or wooden sheets, among others. The *electrical conductors* are overlaid on substrates in various patterns that are printed using conductive inks, e.g., silver inks, silkscreen printed with conductive paints (e.g., nickel-based paint), or made with conductive films (e.g., silver or aluminum-coated polyester films) commonly used in gift wrapping and known under the Mylar® brand name. The *charge-storage* materials are used to store electrical charge, the most commonly used is PTFE−also known under the Teflon® brand name. Finally, *conductive bonding* materials are used for connecting electrical components to Paper Generators or for connecting parts of the Paper Generators. These may be silver-based conductive epoxies or copper tapes with conductive adhesive on both sides. The possibility of using a variety of common materials is an important advantage of our technology, allowing for numerous potential applications.

Designing Paper Generators

Figure 6 demonstrates Paper Generators that we designed. We started with the most basic structures and then designed progressively more complex generators adapting from the pop-up book design mechanics. The designs below were produced using photo paper, and the conductive patterns were printed using a customized Epson WorkForce 30 inkjet printer and Novacentrix® silver-based inks. PTFE films were attached using 3M™ spray adhesive. Conductive silver-based epoxy and conductive copper adhesive tape were used for connecting parts of the Paper Generators and interfacing to the electrical components. Below we present the generator design.

The Tapping Generator converts tapping or pressing on the paper flap into electrical power (Figure 6-1). Tapping or pressing are simple, intuitive gestures that everyone is familiar with through everyday experiences and have numerous uses in interactive applications. The generator utilizes the layered structure described previously: PTFE film overlays a printed electrode on the bottom and a second printed electrode on top, forming a bridge. The electrode on the top is connected to the bottom sheet using conductive tape.

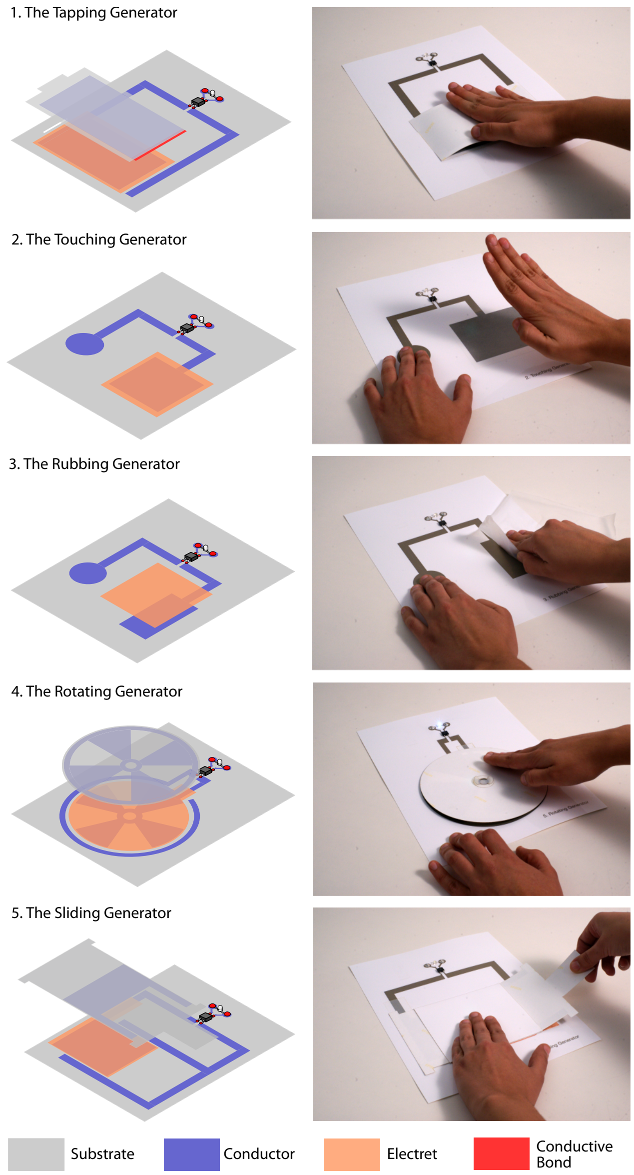

Figure 6. Paper Generators.

When tapped, the top sheet bends and makes contact with the stack, creating a voltage spike. The electrode recoils into its original position when the user's hand is retracted.

The Touching Generator is a variation of the Tapping Generator in which a user taps the bottom PTFE-electrode stack with his or her bare hand, replacing the top electrode (Figure 6-2). The advantage of this design is that it has no moving parts; the circuit is completed through the body by touching the second electrode with the other hand. The human body has enough conductivity to pass high voltages and, because the currents are minuscule, the temporary charges that accumulate in the body are not perceivable.

The Rubbing Generator utilizes a rubbing gesture where the user simultaneously touches one of the electrodes with one hand and rubs the second electrode with a sheet of PTFE (Figure 6-3). The PTFE sheet moves repeatedly on and off the surface of the electrode, creating a change in the induced charge. The principles of its operation are the same as in tapping, except the human hand forms a moving electrode and motion is horizontal rather them vertical. Rubbing generators produce the most power because a rubbing gesture can be performed rapidly with increased pressure, maximizing contact with the electrodes. In fact, because PTFE provides very low friction, users can apply high amounts of pressure effortlessly.

The Rotating Generator is a more complex implementation of rubbing generator. The segmented electrodes are printed on a disk, sliding on and off the bottom electrodes by means of rotation with PTFE film sandwiched in between (Figure 6-4). Unlike with rubbing generator the user does not have to touch a second electrode. To connect electrodes on the top rotating disk to the energy harvesting circuit on the bottom, overlapping circular rails are printed both on the rotating top disk and the bottom sheet (Figure 6-4).

The Sliding Generator is based on the same principle as the rotating generator except it allows power generation by sliding a sheet with a printed electrode on and off the electrode on the bottom sheet (Figure 6-5). Similar to the rotating generator, linear rails are used to connect the top sliding electrode to the harvesting circuit mounted on the bottom.

The designs above demonstrate how basic power generation principles can be used to create new energy generating structures uniquely adapted to specific applications.

Harvesting Circuits

The energy created by the Paper Generator is regulated using circuitry connected between the electrodes. There are two basic strategies to utilize the harvested energy: *immediate* and *charge and release*.

In the *immediate use* strategy, energy produced by Paper Generators is regulated and then immediately applied to an interaction device, such as LEDs or e-paper displays as we discuss later. For regulation, a high-voltage bridge rectifier chip (Vishay Semiconductor, DF10S) is used to convert the AC voltage spikes to a DC signal (see Figure 7a). This DC signal is then connected to an appropriate electrical load. A double-pole, double-throw slider switch is used to reverse the polarity of the output if needed. While the circuit design for this strategy is trivial, because the amount of electrical power generated is very low, its applications are limited.

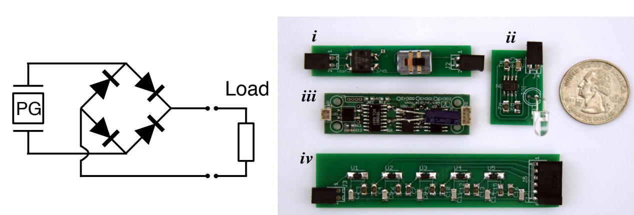

Figure 7. Left: Paper Generator connection to bridge rectifier. Right: the printed circuit boards for (i) rectifier and switch, (ii) IR transmitter (iii) EH301 (iv) zener diode-capacitor array.

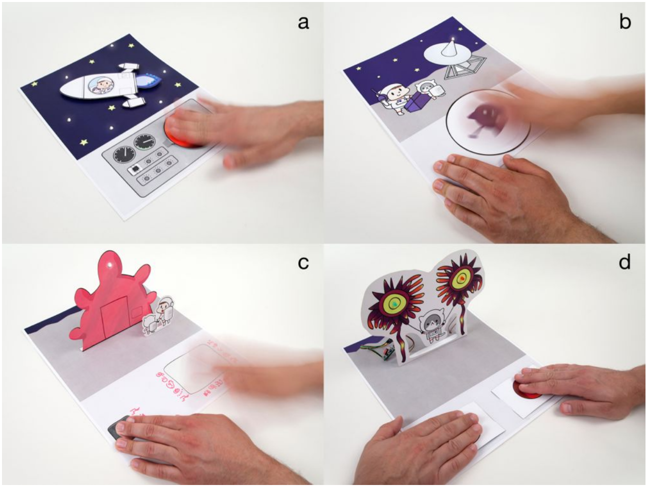

Figure 8. Driving LEDs with Paper Generators

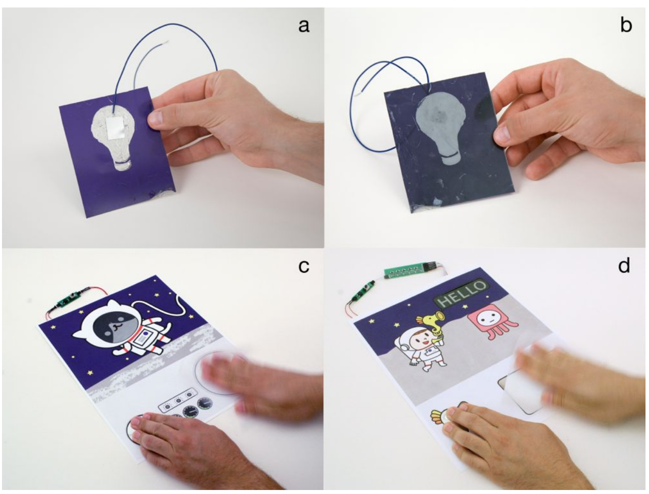

Figure 9. Driving e-paper with Paper Generators

In *store-and-release* harvesting, the electrical energy is used to charge a capacitor and only released to the load when a certain amount of energy is reached. This results in significantly increased power delivery and can be used in applications where a large amount of energy is required, such as a buzzer, or IR communications. To implement this circuit, we incorporate the EH300/EH301 energy store-and-release device from Advanced Linear Devices [1].

APPLICATIONS

We investigated applications of Paper Generators by implementing several interaction scenarios that enhance traditional printed books' storytelling with various output devices, such as LEDs, e-paper displays, sound buzzers, and wireless IR communication, among others. All of the applications that we present can be used with any of the Paper Generators, however, some devices are better suited for some of the applications than others.

LEDs and LED arrays can be very effectively driven by Paper Generators to provide a visual feedback to the user during interaction with the book. In *immediate use* configuration, multiple LEDs are connected in series at the output of the energy harvesting circuit. Because the voltage spikes created by the Paper Generator can reach up to hundreds of volts, it is possible to connect many LEDs in series and have enough voltage drops across each LED to produce bright lights. For example, in Figure 8a the stars and engine of the paper rocket light up each time the user taps on the "power" paper button: the faster and stronger the taps are, the more visible the lights are and, therefore, the "faster" the rocket flies. In Figure 8b, a light on the transmission antenna blinks repeatedly when the user rotates the disk on Rotating Generator, the blinking frequency would depend on the speed of rotation.

In the *store-and-release* configuration the user has to repeatedly rub or tap the generator to accumulate enough energy to flash an LED. It can communicate level achievement and suggest the story progress. For example, in Figure 8c the light on top of the alien house flashes after the user rubs it for a certain amount of time. In another example (Figure 8d), two Paper Generators are combined and readers have to tap on their respective Paper Generators until both alien flowers flash, indicating that the cat is released.

In designing LED-based applications we observed that phosphor-based LEDs, which are generally blue and white, are most suitable as the phosphor allows for prolonged light emission, making it more visible.

Electronic paper (e-paper) displays, such as E Ink's ePaper displays [5], are an especially suitable application for the Paper Generators as they require high voltages but very low switching current and no static power to keep the images on. To create a static image on the e-paper, we apply a layer of conductive epoxy to the back of the e-paper film (Figure 9a). When voltage from the Paper Generators is applied to the hardened epoxy, the image on the front appears (Figure 9b). Very little current is needed to toggle the e-paper display; in the case of rubbing generators a single rub is often sufficient. In Figure 9c, the face of the cat becomes visible when the user rubs the electrode of a Paper Generator.

We can also create simple animations by segmenting the image and connecting the individual segments to Power Generators through a passive capacitor-zener diode array (Figure 7-iv), which allows sequential voltage buildup at different nodes. With this circuit, the letters in a word, e.g., "hello", in Figure 9d, can be made to appear sequentially as more energy is harvested. By switching the polarity of supplied voltage, the letters can be made to disappear.

E-paper displays are some of the most expressive and impressive applications of Paper Generators. Only the bridge rectifier circuitry is sufficient to implement e-paper displays. Building conductive patterns on the back of the e-paper requires careful attention. Indeed, the back of the e-paper film is fragile and damaged easily if conductive patterns are not carefully applied. Furthermore, the film is sensitive to solvents. Many solvent-based conductive materials, such as silver-based tracing pens, cannot be used.

IR communication can be implemented using Power Generators to trigger an external computing device allowing for enhanced paper books with dynamic electronic media. For example, an animation on a screen can be triggered by interacting with a paper book. Store-and-release harvesting configuration is used to power a classic 555 IC oscillator, which then modulates an infrared LED that transmits data to an IR decoder connected to a remote computing device. By varying the frequency of oscillation, we can create unique frequency signatures for different Paper Generators, allowing us to build complex paper-based interactive controllers. In such a scenario any classic paper book can be used to control interactive storytelling on various devices, such as laptops, TVs and tablets.

Sound and mechanical motion can be also created using Paper Generators. For example, we have incorporated a single frequency audio buzzer (Mallory Sonalert, MSR516NR) with the store and release circuitry that creates a buzz, providing the user with an audible response.

In addition, we have incorporated analog voltmeter needles that create mechanical motion. The energy released from the store-and-release circuitry activates the needle. The spring-loaded needles then move back to original position.

DISCUSSION AND CONCLUSIONS

We have presented Paper Generators: a new energy harvesting technology that generates electrical energy from a user's interactions with paper-like materials. The generators can be assembled from off-the-shelf materials, such as PTFE sheets and Mylar, and they can be flexible, light and inexpensive. This paper presented analysis that predicts the current-voltage characteristics of the energy harvester and characterized it through measurements.

We have also defined the basic user gestures and physical structures that allow us to create effective Paper Generators. We evaluated the technology to enhance paper books with simple interactivity. The design is, of course, not limited to books. We envision added interactivity for any printed matter, including books, postcards, posters, board games and many others.

The technology does have certain limitations. The need to implant the initial charge into PTFE is one of the issues that potentially limit the interactive application of Paper Generators. It can be solved by permanently implanting charges into a PTFE sheet using such techniques as corona discharge. We will continue investigating and improving the Paper Generator technology in our future work.

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