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Electrostatic Power Harvesting in Textiles

E. Rehmi Post
MIT Center for Bits and Atoms
Cambridge, MA 02139
e-mail: rehmi@cba.mit.edu

Kit Waal
Electronic Textiles Lab
Asteism, Inc.
Cambridge, MA 02139
e-mail: kitwaal@gmail.com

***Abstract* --- We describe a wearable energy harvesting system based on the phenomenon of contact electrification. By patterning circuits using textiles with specific electronic properties, we can collect and channel charge transferred by contact electrification to power harvesting circuitry. As a demonstration of this principle, we have designed and built a garment to display the wearer's ongoing level of physical activity by powering strings of LEDs using only the energy generated in the garment's motion.**

I. Introduction

In "The Computer for the 21st Century," Mark Weiser suggested that "the most profound technologies are those that disappear. They weave themselves into the fabric of everyday life," [1] yet "ubiquitous computing's dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal." [2] Taken together, these observations underscore a common need for effective and affordable renewable energy sources in many areas of ubiquitous computation and sensing. Therefore it is not surprising that pervasive power harvesting is an active and broad area of research with a wealth of applications in medicine, defense, and consumer electronics. It is also especially relevant to the rapidly growing field of electronic textiles, which has evolved from research curiosities [3] into modular construction kits [4] but still requires conventional power sources to operate.

A strong interest in pervasive power has led to many promising developments including piezoelectric nanofibers [5], photovoltaic wires [6], and variable-capacitance generators [7], to name a few emerging technologies that seem particularly well-suited to harvesting power from ambient energy sources available to e-textile systems.

Unfortunately, most of this work is still in the early stages and presently unavailable for use in practical designs. Therefore we endeavored to develop a novel power harvesting technology that would meet a few simple requirements:

1. Compatibility with electronic textiles and other forms of material computing.
2. Ease of construction using methods and materials available to designers and artists.
3. Exploitation of a well-known, tangible source of power: electrostatic energy.

In the remainder of this paper, we describe the development of Sp4rkl3, a skirt that uses electrostatic energy to harvest enough power from its own motion to light up several LED displays and thus give a continuous indication of the wearer's level of physical activity.

II. Implementation

A. The triboelectric effect

It was not until 1913 that the word triboelectricity appeared in the scientific literature, formed by addition of the Greek root tribos (rubbing), and defined as "electricity generated by friction" [8]. It is worth noting that the etymology and definition of this word are misleading because rubbing is not necessary to transfer considerable charge between materials; often, mere contact will suffice. Contact electrification phenomena occur when nearly any combination of metal (conductor), semiconductor, or dielectric (insulator) materials come into contact, and while their mechanisms are fairly well-understood in metals and semiconductors, there is still considerable debate over the cause of contact electrification in insulators. [9]

B. Identification of materials

To gain a better understanding of triboelectric effects, we developed the simple instrument illustrated in Fig. 1. This triboelectric testing "paddle" is a cardboard panel with three copper foil electrodes, two diodes, and one neon bulb. The electrodes are covered with one triboactive material and the paddle is rubbed against a sample of another triboactive material.

The operating principle of this circuit is deceptively simple and not unlike that of the variable capacitance generator: the diodes allow charge to flow preferentially in one direction across the electrodes, developing a voltage difference across pairs of electrodes. When the breakdown voltage of the neon lamp (typically 100V) is exceeded, a discharge occurs, the lamp lights, and the voltage across the electrode array drops temporarily. This effect is seen clearly in Fig. 2 as a series of spikes as the neon lamp discharges multiple times.

a)
b)
c)

Fig. 1: Triboelectric testing paddle: a) Equivalent schematic; b) Rear of one paddle showing circuitry; c) PTFE on active face of paddle.

To estimate the available power, the output voltage was measured through a 100MΩ series resistance using a Picoscope 2104 USB oscilloscope with a 1MΩ input impedance, giving an effective probe gain of approximately 1:100. Instantaneous power was then calculated as $P(t) = (V(t))^2/(101\ M\Omega)$.

Because charge is stable for a relatively long time on the dielectric surface, the paddle may be thought of as a self-biasing charge pump which harvests energy from motion, or as a type of variable-capacitance generator [7] biased by triboelectric charging instead of an external source.

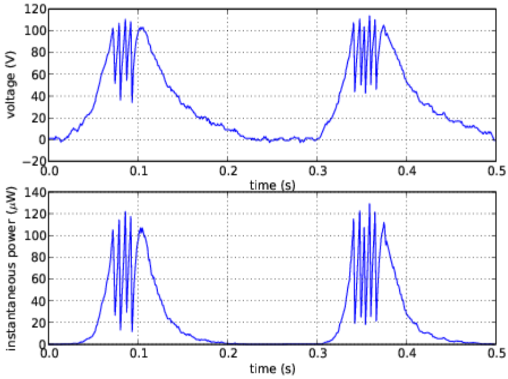

Fig. 2: Voltage and power output of the nylon test paddle as the PTFE test paddle slides from left to right and back over it at a frequency of about 4 Hz; two charging events are shown. Note that charging only occurs for relative motion in one direction. Spikes around the voltage peaks correspond to discharges of the neon lamp across the paddle output. Each charging event has an average energy of 5.6μJ and the average output power is 22.5 μW.

With these paddles in hand, we were able to assay materials at local fabric and hobby stores (e.g. Jo-Ann Fabrics, Fabric Place). While at the fabric store, materials were tested with portable tribopositive (nylon-coated) and tribonegative (PTFE-coated) paddles. As bolts of fabric are not often labeled regarding fiber content, treatments or additives, in-store testing was crucial in determining the triboelectric properties of the materials. Experiments with the paddles on available materials identified rip-stop nylon, vinyl, latex rubber, and 0.003” PTFE film as the best candidates for further work. Rip-stop nylon can be found in most fabric stores and is available online from technical fabric retailers.

C. Prototype skirt panel and display

Encouraged by results from the test paddles, we set out to build a prototype of a panel for the skirt we had in mind. We implemented the same electrode-and-diode ladder circuit used in the test paddles but extended to 10 electrodes, and substituted textiles for the substrate and electrodes. Applique and piecework techniques were used to attached the electrodes, diodes, and terminals to the substrate. An inside view of the prototype panel is shown in Fig. 3.

Fig. 3: Inside view of prototype skirt panel. 10 electrodes (each approximately 2.5 cm×10 cm) were cut out of conductive organza and affixed to the nylon substrate using spray fabric adhesive. Diodes were soldered to sections of copper braid and sewn across the organza strips. Two additional sections of copper braid were sewn to the terminal electrodes to allow connection to external circuitry.

Power measurements were performed using the same probe gain (1:101) and loading (101 MΩ) as before. A 16 cm×16 cm square of PTFE was rubbed lightly back and forth across the outer surface of this panel and the output voltage was monitored directly, with a typical charging cycle seen in Fig. 4.

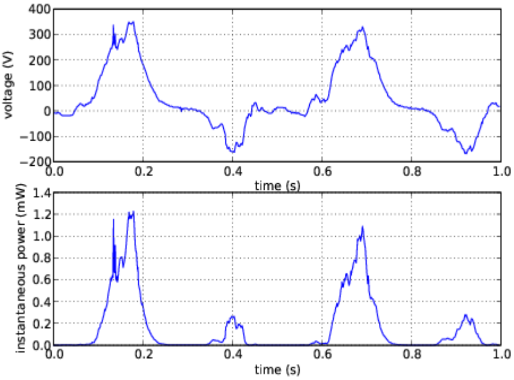

Fig. 4: Voltage and power output of prototype nylon skirt panel as a PTFE sheet is rubbed (with light pressure) back and forth at a frequency of about 2 Hz across the vertical centerline of the panel as pictured above. Four charging events are shown, and a strong asymmetry is visible in the output voltage due to the diode ladder. Average output power over the entire 1 s interval is 162.2 μW.

We also developed a simple energy-harvesting circuit and multiple LED display, shown in Fig. 5. Diacs S1 and S2 maintain a bias voltage between 100V and 200V across the electrode array and C1 provides a charge reservoir. Diodes D1-D4 form a full-wave rectifier that drives a string of LEDs. By putting 40 red LEDs in series, each with a nominal forward voltage of $V_f \approx 2$ V we were able to avoid the need to step down the high output voltage ($V_{out} \approx 100$ V).

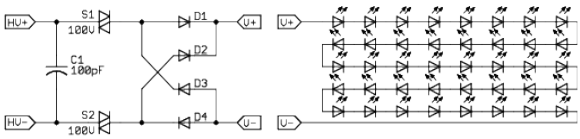

Fig. 5: Schematic of prototype energy harvesting circuit and LED display.

D. Production skirt panel and display


Fig. 6: The Sp4rkl3 skirt. [photo credit: Mikey Siegel].

The final skirt is shown in Fig. 6. Six pairs of panels were constructed. Red rip-stop nylon was used for the electrode substrate, while black rip-stop nylon was used for the outer covering. The diode/electrode ladder pattern of the prototype was extended to a total of 16 electrodes arranged as in Fig. 7. The inner triboelectric panels were made of two layers of 0.003” PTFE sandwiched around a layer of conductive organza. The organza was first stabilized by hemming the edges and then affixing to one sheet of PTFE with spray adhesive. The second PTFE sheet was then added and a whipstitch hem was placed around the edge. Care was taken not to allow the needle or thread to crack the PTFE. Weight-bearing seams (across the top of the panel) were reinforced with stiff interfacing.

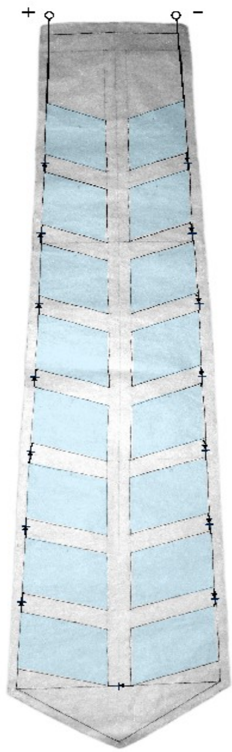

Fig. 7: Sp4rkl3 skirt panel pattern. Panels were fabricated using similar materials and techniques as in the prototype panel but on a larger scale (16 electrodes with a total area of about 156 in^2 ($\approx 0.1\ m^2$). Terminal electrodes (+ and -) were fabricated of folded conductive organza to make robust sewable attachments.

Electrodes can be glued onto a backing fabric as long as the glue doesn't fully encase the areas of the electrode contacting the triboactive surface. This also has the benefit of minimizing fraying, a source of electrical shorts. Each of the six tribogenerator panel pairs attaches by fabric snaps to its own circular power harvesting circuit and LED display (referred to as a medallion). These medallions were fabricated on single-sided 0.010" FR4 PCB stock using a toner transfer and chemical etch process. A schematic of the medallion is shown in Fig. 8. Note that while the HV+ and HV- terminals are attached to either side of the electrode/diode ladder, a third common terminal (COM) has been added to connect to the conductive fabric ground plane in the PTFE panel. Bias is maintained at around 100V by diacs S1-S3 as before, and diodes D1-D6 form a three-phase full-wave rectifier. Finally, a capacitive link to the common terminal has been added to the center of the LED string. The common ground planes of the six generators are connected to shield the wearer from unintentional discharges.

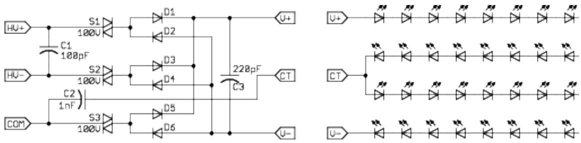

Fig. 8: Schematic of the Sp4rkl3 skirt LED medallion.

The addition of a common terminal to the power harvesting circuit and display allows it to display three distinct charging events. When the voltage across the electrode array causes any pair of diacs to conduct, the entire string of LEDs (from V+ to V- terminal) will light up. In addition, as the panels separate and come together they act as a variable-capacitance generator and light up alternate halves of the LED string (from V+ to CT or CT to V-) according to the direction of current flow.

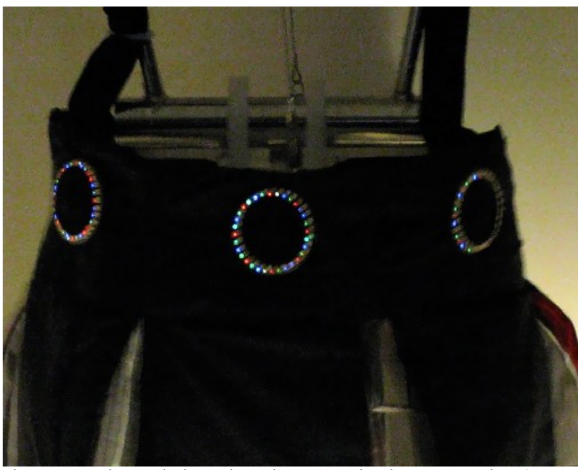
Fig. 9: Sp4rkl3 lighting up when shaken by the motorized mannequin (see text for explanation).

III. Results

A. Performance

A simple measurement of the final power harvester's performance was done by measuring the voltage drop across a 1 kΩ resistor inserted between the CT terminals of the circuit shown in Fig. 8. Fig. 10 shows the result of a typical charging cycle as the inner and outer panels are separated by 1 cm and brought back into contact. The measured current through the load resistor was converted to a power measurement and numerically integrated to arrive at a total energy of 657 μJ per charging cycle or an average power of 1.3 mW under these test conditions.

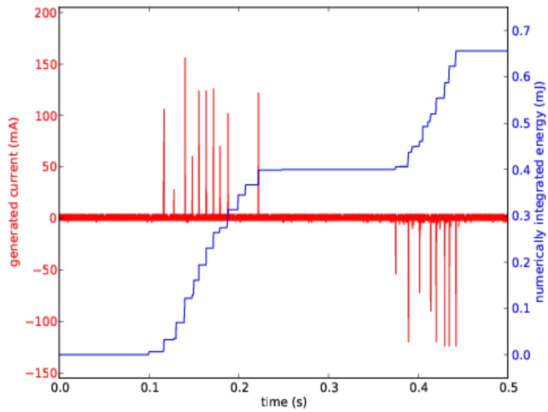

Fig. 10: Charging event in one skirt panel

B. Durability

The Sp4rkl3 skirt is also a durable artifact. It was exhibited at the Boston Museum of Science for 12 weeks between November 2008 and February 2009 . It was mounted on a mannequin that had been modified to include a motorized waist to shake the skirt. The stepper motor was programmed to rock the waist sharply 3 times from front to back in 2 seconds through a total arc of about 10 degrees, followed by a pause of 1 second every time an attached button was pressed. The entire assembly was suspended from the ceiling of a display vitrine. As the display was in a high-traffic area of the museum, we estimate that the button was pressed approximately 17,000 times during this period (twice every five minutes during opening hours) and therefore the skirt was shaken more than 50,000 times. After the period of this exhibit, neither the performance nor the structural integrity of the skirt were noticeably degraded.

IV. Contributions and next steps

We have demonstrated a scalable architecture for triboelectric generation of power in textiles, including:

- Implementation of variable-capacitance and electrostatic-induction generators in textiles.
- Use of triboelectric properties as a charge source for such generators.
- Hand-crafting such generators in wearable form using standard craft materials and techniques.

By combining a multi-mode mechanically-driven charge pump with a triboelectric charge source, we have achieved higher conversion efficiency than would be possible with either approach alone. This work has been implemented in a wearable form to recover power from the wearer’s motion. Power can be harvested from multiple modes of motion, particularly surfaces sliding over one another as well as surfaces moving together and apart.

These principles are not limited to fabrication in clothing and may be applied to many other media including packaging, enclosures, print media, carpeting, and building construction media to name a few. There are also applications to semi-passive mechanical actuation by selectively harvesting energy from a system's motion in order to cause it to slip and stick as desired.

The major risk is in this work going forward is that triboelectricity is known to be a difficult phenomenon to model, predict, and control. Furthermore, the majority of current research into triboelectric phenomena seeks to minimize or mitigate its effects, whereas we have sought to maximize and channel these effects. Major areas of work remaining to be done include:

1. Efficient conversion of output power to voltages compatible with standard low-power electronics.
2. Optimization of triboelectric charging and electrostatic induction.
3. Implementation of nonlinear charge pump components (e.g. diodes) as all-fabric or printed structures, and/or development of semiconductor packages compatible with fabric systems.

V. Acknowledgments

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