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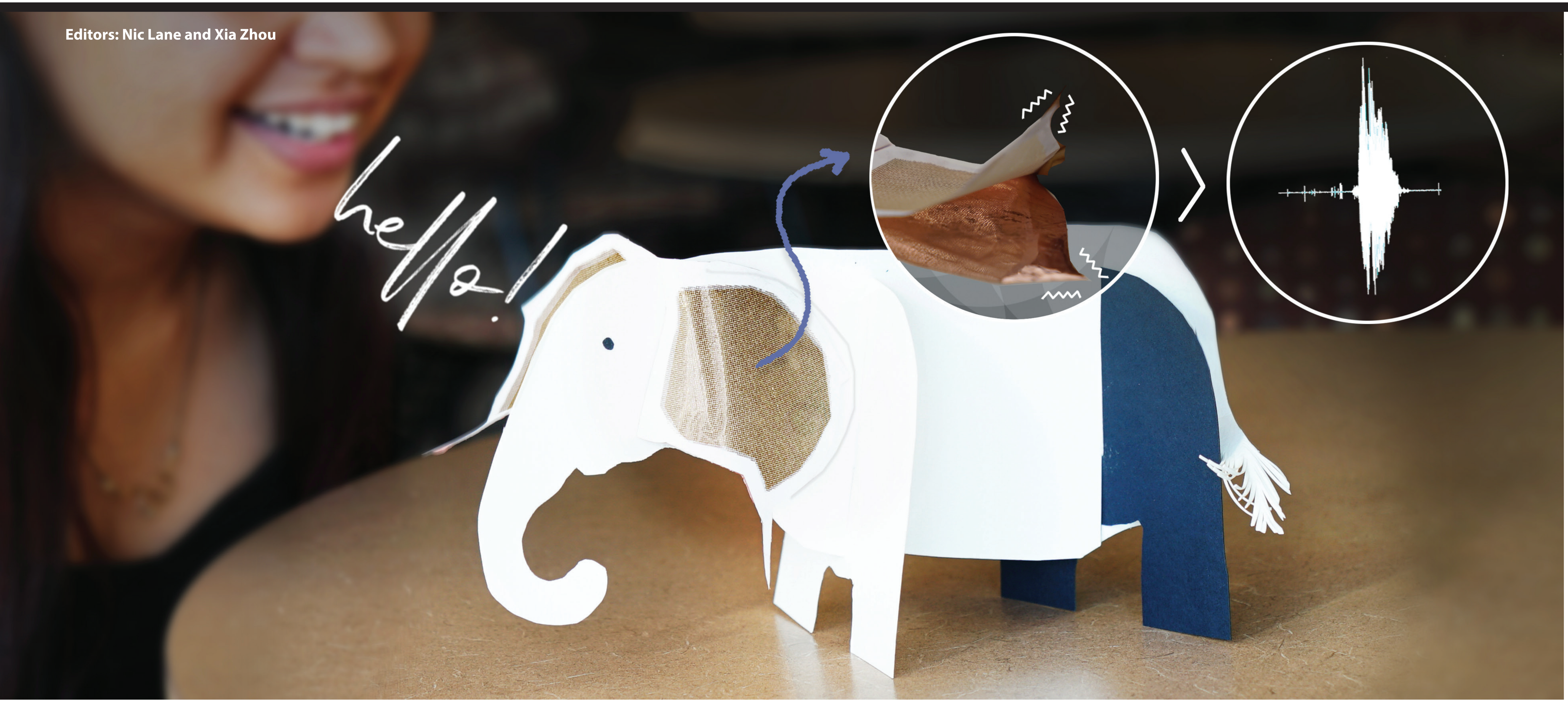

SATURN:
Technical and Design Challenges of Building a Self-sustaining Sound and Vibration Sensing Material

Excerpted from "SATURN: A Thin and Flexible Self-powered Microphone Leveraging Triboelectric Nanogenerator," from *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* with permission. https://dl.acm.org/citation.cfm?id=3214263 © ACM 2018

SATURN is a thin and flexible multi-layer material that can sense sound and other mechanical vibrations in the environment without any external power source. It is constructed of inexpensive materials (paper, copper, and plastic), so that it can be attached to a variety of objects and surfaces. When flat, SATURN's frequency response below 5000Hz is comparable to a powered microphone. When bent, SATURN has a comparable frequency response up to 3000Hz. As a sound power harvester, SATURN can harvest 7 microWatts, which allows the detection of loud sound events. We explore the space of potential applications for SATURN as part of self-sustaining interactive systems.

What if a paper-like material could sense and transmit sound and other mechanical vibrations wirelessly? Imagine an early morning scene in Sal's household. Sal has installed a single voice home control device in her living room with paper microphones at different places to extend remote interactions. Sal gets up hearing the alarm sound from the smart home device and double taps the sticky-note paper microphone on her bedpost to stop it. She goes to her closet to dress for the day, unsure yet about the weather. Sal asks the microphone sticky note on her closet wall about the temperature outside. Next, as she comes out to the living room, she hears the voice of her 7-year-old child on the home assistant, calling for her via the paper microphone placed on his toy elephant. She goes to check on him as her husband arrives from his workout to open the main door using a unique password combination of blows and taps. The smart home device recognizes his arrival and announces that he is home. To make this scenario a reality, where a disposable paper-like material can sense mechanical vibrations, such as voice, taps, and blows, we built a wireless audio sensing and communication material: **SATURN** (**S**elf-powered **A**udio **T**riboelectric **U**ltra-thin **R**ollable **N**ano-generator) [2]. SATURN is thin and flexible in form factor, cheap to manufacture and self-sustaining in its power consumption. It has comparable signal quality to active microphones that consume power and are more expensive and bulky.

HOW SATURN WORKS

Recent advances in materials science demonstrate the possibility of self-powered, easy-to-manufacture sensors that take advantage of the triboelectric nanogenerator (TENG) effect, which converts mechanical vibrations into electrical energy [4,6]. When made in the right form factor, these mechanical energy generators could be manufactured as self-sustaining sound and vibration sensors. We use these principles for the design and fabrication of SATURN, as explained below.

Principle of Working: Triboelectric Nanogenerator (TENG)

When two different materials come into contact and separate, or rub alongside each other, they tend to either gain or lose electrons, based on their position relative to each other in the triboelectric series [8]. This common phenomenon of exchange of electrons is called triboelectrification. The redistribution of charge creates an electric potential between the layers. If there is a conductive path between the two layers, the charge difference will balance due to electrostatic induction. Repeated contact and separation, therefore, produces an alternating current [5]. This multilayer structure, consisting of different materials that are both conductive on one side, is called a Triboelectric Nanogenerator (TENG).

Device Design

SATURN is an example of a TENG and consists of two layers (Figure 1). The first is the copper that acts as a triboelectrically positive material. This layer is coated onto paper for mechanical support. Paper is low cost, flexible, light, and easy to perforate, making it a favorable medium to support vibration in the presence of sound waves. The second layer is a dielectric plastic, PTFE(Polytetrafluoroethylene). It is a triboelectrically negative material coated with copper on one side. The first and second layers are placed with the copper side of the paper touching the non-copper-coated side of the PTFE. The layers are anchored to each other using glue in a specific grid dot pattern. A potential difference is caused by vibration and is measured between the two copper-coated surfaces.

SATURN IS AN EXAMPLE OF A SELF-SUSTAINING WIRELESS MECHANICAL VIBRATION AND SOUND SENSING COMPUTATIONAL MATERIAL

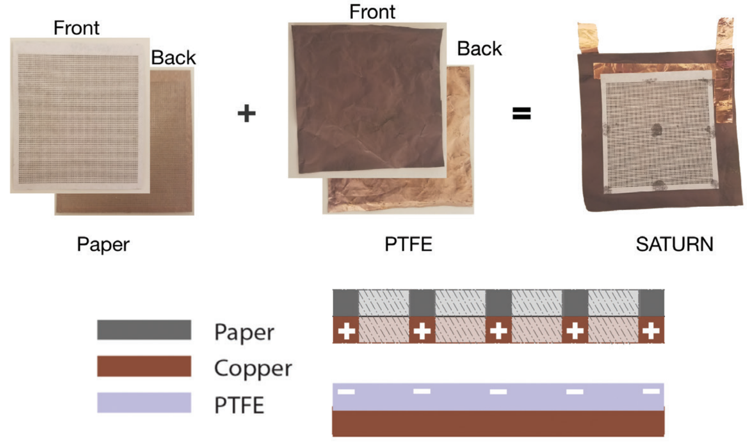

FIGURE 1. SATURN device design: Multiple layered structure of SATURN, consisting of paper with holes coated with copper (triboelectrically positive material) and PTFE (triboelectrically negative material) coated with copper.

Mechanism

This section explains how the change in air pressure due to sound vibrations causes constant contact and separation in the multilayer structure of SATURN. When the two layers of SATURN, paper and PTFE, come in contact with each other, charges are induced in the copper and the PTFE due to triboelectrification (Figure 2a). PTFE has a greater electron affinity and gains electrons from the copper to become negatively charged. In parallel, the copper layer on the paper becomes positively charged. The subsequent separation of the paper and the PTFE (Figure 2b) induces a potential difference across the two copper electrodes. Such a separation causes current to flow from the paper towards the PTFE layer when the device is connected to an external load. This flow of current reverses the polarity (Figure 2c) of charges on the two copper electrodes (i.e., now the copper on PTFE has more positive charge than the copper layer on the paper). The next compression results in a reversal of the current flow (Figure 2d) from the paper towards the PTFE layer to complete the cycle of electricity generation.

Device Optimization

We have optimized different device design parameters in SATURN's structure to increase its electrical response across a wide frequency of the audible range. Different structural design parameters (Figure 3) – the hole size and spacing of holes in paper, the geometry of the patch, and the glue points to attach the two layers – are varied to understand their effect on signal quality, to finally come up with a design that is both reliable and replicable.

PERFORMANCE

Self-sustaining Sound Sensor

After optimizing SATURN's structural parameters, we are able to reach the best acoustic sensitivity of -25.63 dB (re mV/Pa) at 1000 Hz with a circular shape of 16 cm^2 area with a grid pattern of holes of 0.4 mm diameter and 0.2 mm spacing glued at 8 equally distant points around the edges and the center to the PTFE. In this configuration, the SATURN microphone has a comparable frequency response from 20-5000Hz to an active microphone (Figure 4). Approximately 90% of the information related to human voice is within this range, making SATURN a good quality microphone for a variety of applications. The acoustic sensitivity of SATURN when bent reduces with increasing bending angle due to the increase in stiffness of the structure which results in lesser vibration of the layers. At a bending angle of 45 degrees, SATURN is still a usable microphone and comparable to an active microphone till 3000 Khz, allowing capture of more than 60% of sounds associated with voice.

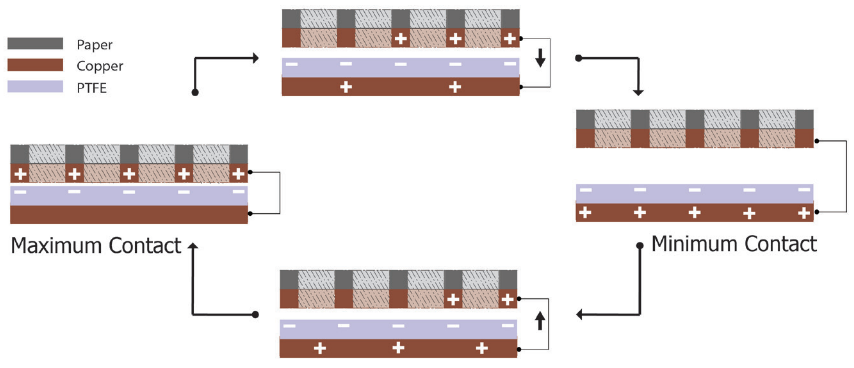

FIGURE 2. Cycle of electricity generation process in SATURN under external acoustic excitation due to the combined effect of triboelectrification and electrostatic induction.

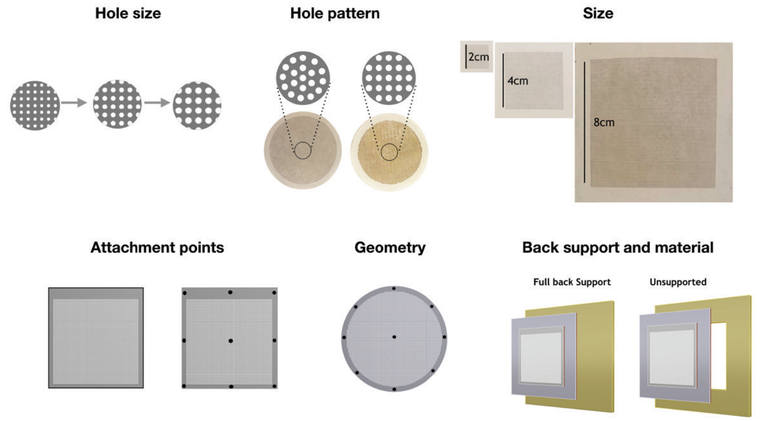

FIGURE 3. Structural device design optimization.

Sound Energy Harvester

SATURN in the presence of loud sound can harvest enough energy that could be used for doing computational tasks. We analyzed the 4x4 cm^2 SATURN microphone patch as a power harvester under loud sound pressure (100 dB). For a 1 Mohm load, SATURN generates approximately 0.5 Vpp at 150 Hz, which rises to a maximum at 2.5 Vpp at 250 Hz and then falls below 1.0 Vpp at 350 Hz. The same behavior is shown in the power curve, with 6499 nW being the maximum power that can be harvested at 250 Hz.

SELF-SUSTAINING COMPUTATIONAL SYSTEM

In the previous section, we saw the characterization of SATURN as both a self-sustaining microphone and an energy harvester. To use SATURN in a practical application, it needs to be embedded in a self-sustaining computational system that can allow a transfer or storage of the data. Figure 5 shows how a tag consisting of SATURN, a transistor, and a flexible antenna can leverage radio backscatter technology to passively communicate sensed sound or vibration information [1]. Figure 6 demonstrates how SATURN, when in the presence of a loud sound, generates enough power that it can support flipping of a bit in flash memory, which can be interrogated later using radio waves [2]. In an alternate method, if the loud sound is persistent for a few seconds, it can be used to activate a low-power long-range radio [3], which allows for real-time communication of loud acoustic events.

EXPLORATION OF APPLICATIONS

The thin and flexible form factor of SATURN allows it to be placed on different surfaces for self-sustaining audio sensing applications (Figure 7). We imagine scenarios where many different inexpensive SATURN patches in the home can extend the range of audio input for home assistants. In addition to speech sensing, SATURN can also be used as a contact microphone to sense simple input touches, such that different force of taps could be detected. In more industrial environments, SATURN can be used for acoustic failure monitoring and diagnostics in places where it is difficult or dangerous for humans to access. For example, SATURN patches might be placed on turbines in a nuclear power plant to monitor them for vibrations that indicate damage or wear. SATURN as a loud sound power harvester could be used for inexpensive, battery-free ambient monitoring of sources of noise pollution. Applications include monitoring for sound thresholds exceeding human hearing tolerance, such as in construction zones, mines, music venues, power stations, airports, spaceports, and military environments. Similarly, SATURN-based sensors might be used for monitoring events, such as landslides and mine gas explosions.

CHALLENGES AND FUTURE WORK

This section gives an overview of some of the challenges faced and future work for this project to make it more concrete and deployable in real-life scenarios.

1. **System Challenges:** SATURN is an early prototype for the paper microphone scenario from Sal's home. There is a need to work on the robustness of the radio backscatter architecture for the communication of data. Large scale deployment of such sensors requires us to create innovation on both the hardware and the software side to be able to distinguish different devices in a single room. In addition, there is a need to incorporate privacy-aware design principles and come up with both innovative technological and social approaches to ensure user control over when and where a SATURN patch senses and transmits data. For example,

SATURN microphone patches could be constructed at a physical level that requires tapping a finger on it to prime the backscatter circuit before audio could be transmitted (e.g., when a speaker taps a microphone to ask, "Is this mic on?"). Furthermore, the patch can be constructed to have a limited sensing range for the human voice. Another way to design SATURN for privacy is to tune the resonant frequencies of the patch to focus on only certain types of sound or vibration, excluding the human voice.

2. **Design Challenges:** SATURN is a computational material that looks more like paper and inspires creative uses, such as being used as part of papercraft. Computation that looks and feels more like everyday objects will change the way that we as humans experience, understand and build relationships with that technology. It also creates opportunities and challenges for infusing computation with values, such as sustainability, through the deliberate choice of materials used to create a computational effect.

3. **Manufacturing Challenges:** In an ideal situation, we would like these paper microphones to be cheap and disposable, so we would not worry if they are lost or stolen. Currently, the bill of materials for a single sticky note-size SATURN microphone is less than a cent, but its manufacturing cost is still high due to the way we are depositing copper on paper and PTFE. This pushes us to think about the manufacturing process, so it can be scaled. When SATURN is placed in a self-sustaining computational scenario, the cost gets higher, depending on the active transistor component being used. This expense begs the fundamental question: does our traditional semiconductor industry provide the support needed for large-scale ubiquitous sensing? How can we change our traditional manufacturing techniques to be able to support applications where objects and surfaces have computation embedded in them?

4. **Need for Multi-disciplinary Mindset:** Building SATURN involves solving technical, system-level and design challenges, which span many fields.

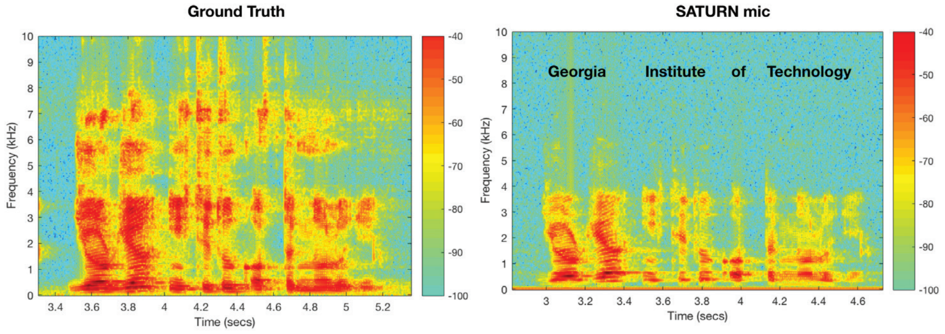

FIGURE 4. Spectrogram of speech signal recorded simultaneously by iPhone and SATURN microphone. The acoustic sensitivity of a 16 cm² SATURN patch is comparable to an active microphone in acoustic sensitivity till 5000Hz.

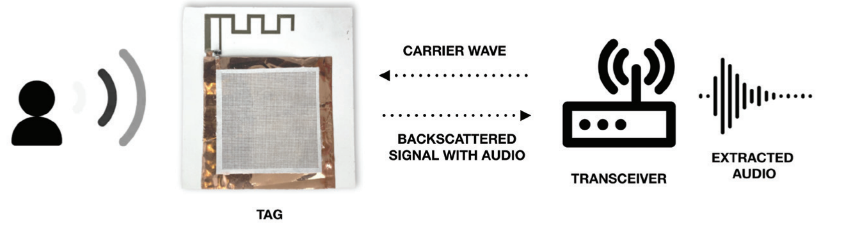

FIGURE 5. Self-sustaining computational systems for SATURN as a sound sensor.

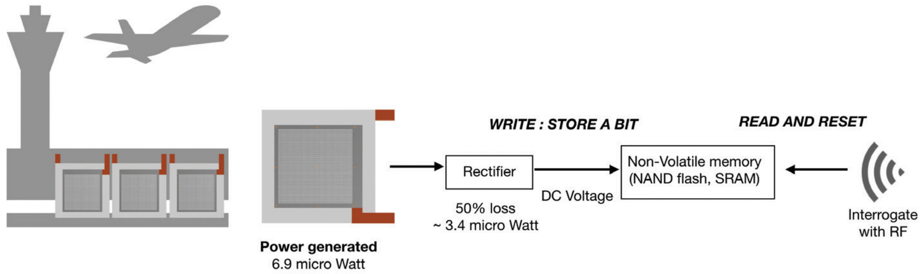

FIGURE 6. Self-sustaining computational systems for SATURN as a loud sound energy harvester.

Materials science is required to design SATURN patches; mechanical engineering helps characterize the effect of vibration on a patch; wireless, low-power electronics is necessary for building self-sustaining communication; flexible electronics are required for manufacturing the prototype, and design and HCI knowledge help us explore applications in everyday settings. Using a combination of self-sustaining sensors and backscatter technique, there is an opportunity for creating thin wireless sensing solutions for many different phenomena. Developing them will require researchers who can adopt an aggressively multi-disciplinary mindset to collaborate and learn the language of many different fields.

CONCLUSION

SATURN is an example of a self-sustaining wireless mechanical vibration and sound sensing computational material. Its simple multilayer construction results in a computational device that resembles everyday materials. It looks and feels like paper, yet it behaves like a wireless microphone. Using power (requiring no external power source), cost (large-scale manufacturing with simple materials), and form factor (looking more like everyday objects) as driving factors in the design of computational devices can lead to a whole new generation of interesting computational materials. These materials may finally allow us to create technologies that, in the words of Mark Weiser, "weave themselves into the fabric of our everyday lives until they are indistinguishable from it." [7] ■

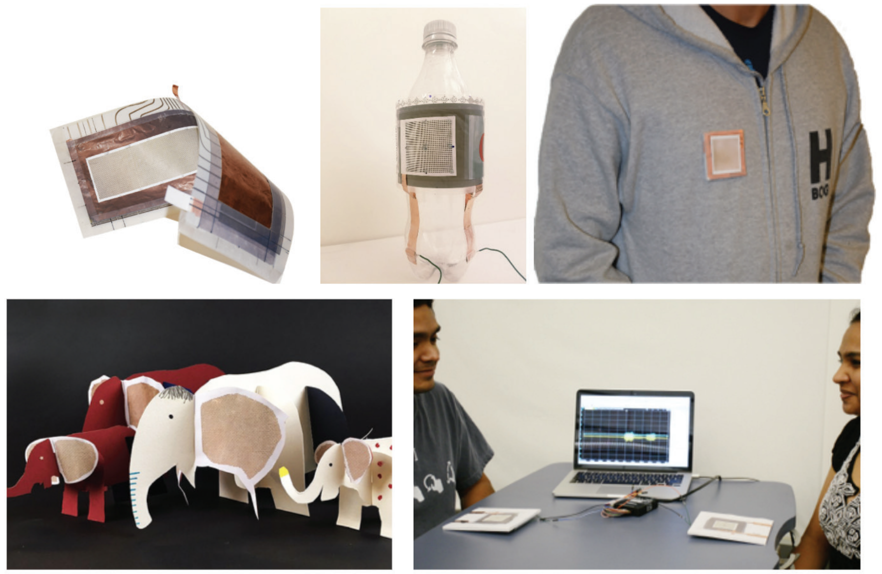

FIGURE 7. SATURN is flexible and can be made in different shapes and sizes, allowing instrumentation of everyday objects, such as a soda bottle, shirt, and paper crafts for interaction, control, context sensing, and event detection applications.

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