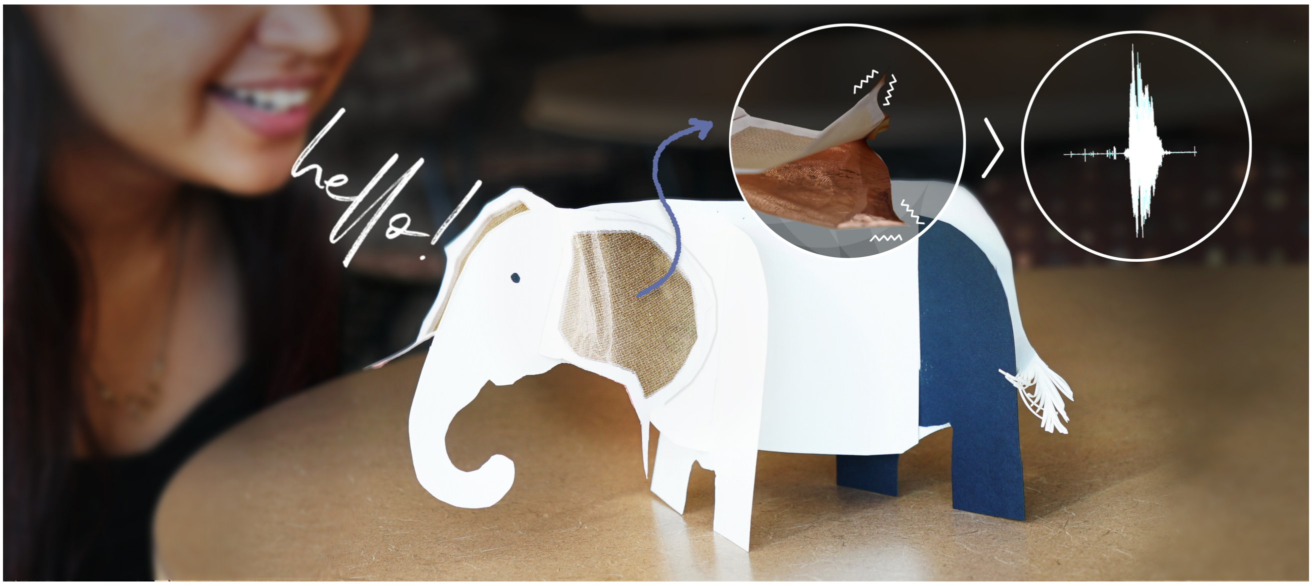
SATURN: An Introduction to the Internet of Materials



Sound impacts the SATURN vibration sensor, which is formed in the shape of the elephant's ear. SATURN's triboelectric components vibrate (inset), generating an electrical signal.

Nivedita Arora, Thad Starner & Gregory D. Abowd
School of Interactive Computing
Georgia Institute of Technology, USA
{nivedita.arora,thad,abowd}@gatech.edu

ABSTRACT

We envision a new generation of computation devices, *computational materials*, which are self-sustaining, cheaply manufactured at scale and exhibit form factors that are easily incorporated into everyday environments. These materials can enable ordinary objects like walls, carpet, furniture, jewelry and cups to do computational things without looking like today's computational devices. SATURN (Self-powered Audio Triboelectric Ultra-thin Rollable Nanogenerator) is an early example of a computational material that can sense vibration, such as sound. SATURN can be manufactured from inexpensive components, is flexible so that it can be integrated into many different surfaces, and powers itself through the sound or vibration it is sensing. Using radio backscatter, we demonstrate that SATURN's sensed data is passively transmitted to remote computers, alleviating the need for batteries or any wired power for the material itself. The proliferation of these types of computational materials ushers an era of Internet of Materials, further blurring the distinction between the physical and digital worlds.

1. INTRODUCTION

> The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it. [18]

This poetic and mostly metaphorical vision from Mark Weiser inspired nearly 30 years of ubiquitous computing research. Weiser correctly predicted an era of proliferation of many differently sized devices aimed at augmenting our human experience with technology. Today's realization of ubiquitous computing devices—smartphones, tablets, electronic whiteboards, wearables—are still fairly easy to distinguish from everyday objects in the physical world. Sizes may vary, but there are still very distinctive characteristics of something that is computational. The Internet of Things (IoT) has tried to hide computing into more and more everyday objects, like light bulbs, television sets and speakers, but we are still far from a complete blurring of the physical and digital worlds. To make something computational still requires "smarts" composed of off-the-shelf integrated

---

The original version of this paper is entitled "SATURN: A thin and flexible self-powered microphone designed on the principle of triboelectric nanogenerator" and was published in Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 2.2 (60), 2018, ACM

circuits housed in rigid modules that are packaged with existing objects. Computing is too separate from the materials of everyday objects. We propose a different direction based on Weiser's vision, that is, starting with the materials of everyday life and creating computation from there. In doing so, we propose an **Internet of Materials (IoM),** where the very materials of objects and surfaces are augmented or manufactured to have computational capabilities. This recasting of ubiquitous computing as "computational materials" presents three major challenges:

- **Power:** Computational materials should be self-sustaining in terms of power consumption. They should not require a wired, constant power source or battery replacements. Instead, they should be able to harvest power from the environment for operation. We would never want to plug in an everyday object, like a cup, nor do would we ever want to worry about replacing a battery or recharging it.
- **Cost:** Computational materials should be cheap to manufacture at large scale. Despite progress in manufacturing increasingly complex and powerful integrated circuits, as dictated by Moore's Law, we cannot afford to make computational materials the same way. It would be too expensive and would not scale to cover entire buildings, outdoor surfaces, or clothing.
- **Form Factor:** Computational materials should be flexible or dispersible such that they can be easily integrated into everyday objects and surfaces. The key to blurring the physical and digital worlds is to make the digital objects look and feel more like physical objects.

For several years, we have been driving our research with these three challenges. We present here one of our first successful examples of a computational material, **SATURN** (**S**elf-powered **A**udio **T**riboelectric **U**ltra-thin **R**ollable **N**anogenerator). SATURN is a demonstration of a thin and flexible multilayer material for detecting mechanical vibrations, which are ubiquitous in our everyday environment. Inspired by recent results in materials science, SATURN produces energy from mechanical vibrations using a truly ubiquitous phenomenon which occurs between any two different materials rubbing against each other. We show how this fundamental property of materials can be turned into a self-sustaining sensor and then demonstrate how other simple materials can be used to help turn the sensor into a wireless sensor.

We outline the paper in 6 main sections. Section 2 introduces the design and working principles of SATURN. Section 3 characterizes SATURN as a self-sustaining microphone and loud sound energy harvester. It is followed by Section 4 which demonstrates different ways of building a self-sustaining computational system leveraging SATURN. Next we discuss applications in section 5 some of which are implemented and some are exploratory in nature. In Section 6 we discuss how this work impacts our thinking in developing computational materials.

2. SATURN: WORKING PRINCIPLES

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 [14, 16, 17]. 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, fabrication and evaluation of SATURN [3], a flexible, self-powered sound sensor and sound energy harvester that is constructed with thin and inexpensive materials. The novelty of the work lies in creating a device that considers power, cost and form factor as central design parameters without sacrificing signal quality.

2.1 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 [21]. 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 [15]. This multi-layer structure, consisting of different materials that are both conductive on one side, is called a Triboelectric Nanogenerator (TENG).

2.2 Device design and fabrication

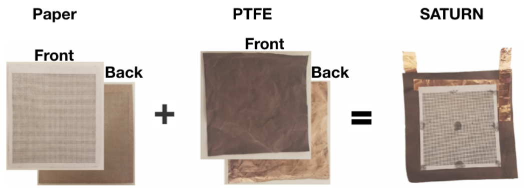


Figure 1: Structural design of a SATURN microphone consisting of copper-coated paper and PTFE

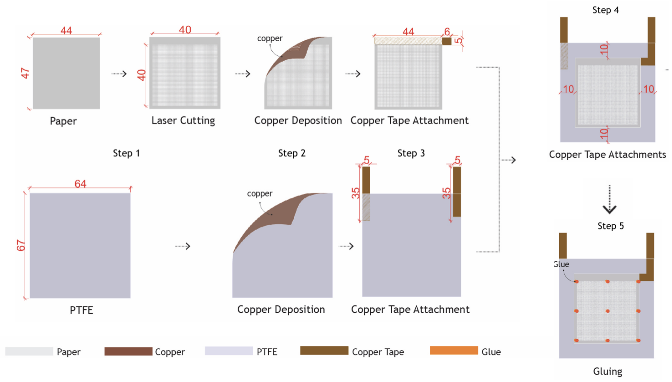


Figure 2: Fabrication process: (1) Preparation of micro-hole paper (2) Deposition of copper layer (3) Attaching copper tape as electrodes (4) Stacking paper and PTFE (5) Gluing paper and PTFE. All dimensions are in mm.

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 and is coated onto paper for mechanical support. Paper is used because of its low cost, while its flexibility, light weight and ease of perforation all support its vibration in the presence of sound. The second layer is a dielectric plastic, PTFE (polytetrafluoroethylene), that acts as a triboelectrically negative material and is coated on one side with copper using physical vapor deposition. The first and second layers are placed on top of each other, 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 with a specific dot pattern. A potential difference is caused by vibration and is measured between the two copper-coated surfaces (see Figure 2).

SATURN's structural design is tuned to increase its electrical response across a wide frequency range. Structural design parameters (Figure 3) such as hole size and spacing, the geometry of the patch, and the glue points attaching the two layers are varied to understand the effects on signal quality using a combination of evaluation techniques. These parameters are optimized empirically based on measured voltage generated by the microphone at a standardised decibel level and by using a mechanical model simulation that compares the separation distance between the two layers of SATURN when vibrating.

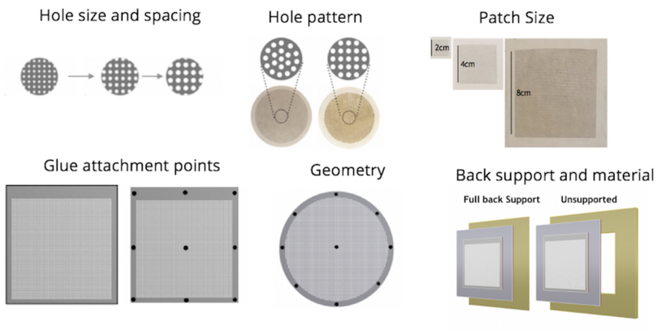


Figure 3: SATURN's structural design parameters

2.3 Operation

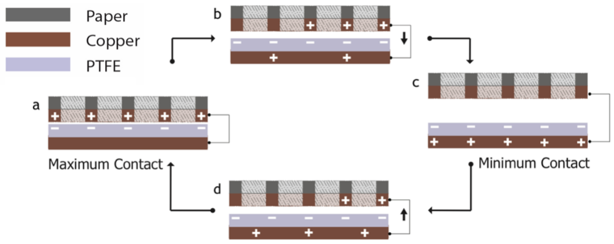


Figure 4: Cycle of electricity generation process under external acoustic excitation

Change in air pressure due to sound vibrations causes constant contact and separation in the multilayer structure of SATURN. When the two layers are in contact with each other, charges are induced in the copper and the PTFE due to triboelectrification (Figure 4a). PTFE, which has a greater electron affinity, is able to gain electrons from the copper and becomes negatively charged, whereas the copper layer on the paper becomes positively charged. Subsequent separation of the paper and the PTFE (Figure 4b) induces a potential difference across the two copper electrodes, causing current to flow from the paper towards the PTFE when the device is connected to an external load. This flow of current reverses the polarity (Figure 4c) 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 the paper moving towards the PTFE again, resulting in a reversed direction of current flow (Figure 4d), completing the cycle of electricity generation.

3. PERFORMANCE CHARACTERISATION

3.1 self-sustaining microphone

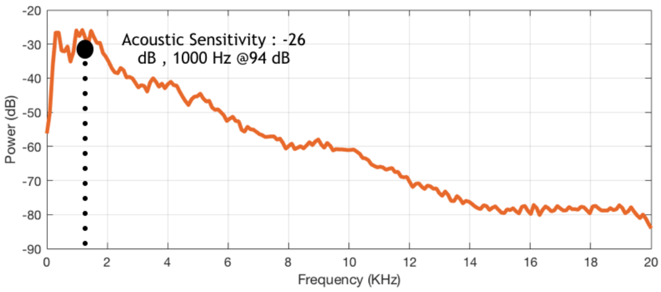


Figure 5: Sensitivity across acoustic bands (20 Hz - 20 kHz)

Even though SATURN is self-sustaining, flexible and thin, its quality as a sensor is comparable to an active microphone that consumes power. After structural optimizing SATURN, the best acoustic sensitivity of -25.63 dB (relative mV/Pa) is achieved at 1000 Hz. The resulting SATURN patch has a circular shape with a 16 cm^2 area, a grid pattern of holes 0.4 mm in diameter with 0.2 mm spacing, and glue attachments of the two layers at the center and at eight equally distant points around the edges of the PTFE (Figure 5). In this configuration, the SATURN microphone compares favorably to an active microphone (MEMS ADMP-401 and iPhone INMP441) for frequencies as high as 5000 Hz (Figure 6). Since approximately 90% of the acoustic information for human speech lies within this range [4], SATURN can be used a good quality microphone for a variety of applications.

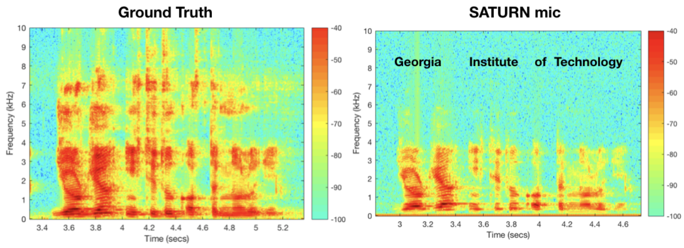


Figure 6: Acoustic sensitivity of SATURN sensor compared to an active microphone

Bending of SATURN reduces the acoustic sensitivity as the bend angle increases due to the increase in the 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 is comparable to an active microphone up to 3000 kHz, allowing capture of more than 60% of the sound information of speech [4]. See Figure 7.

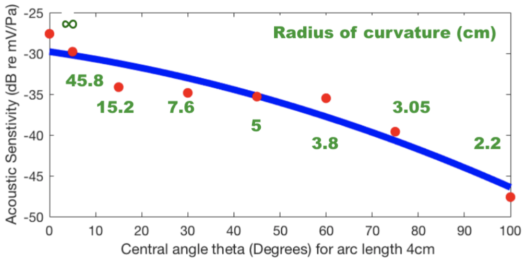


Figure 7: Experimental results for the effect of flexibility: Change in acoustic sensitivity (1000 Hz at 94 dB obtained for different radii of curvature)

3.2 Loud sound energy harvester

Next we look at SATURN as an energy harvester for loud acoustic events. We performed an experiment to determine the peak voltage and peak power of the SATURN microphone at its resonant frequency as functions of an external load resistance. We analyzed the 4x4 cm^2 SATURN microphone patch as a power harvester when exposed to loud sounds (100 dB). The voltage is approximately 0.5 Vpp at 150 Hz and 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 a maximum power of 6499 nW (Figure 8).

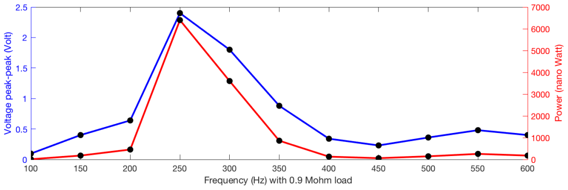


Figure 8: Voltage and power generated at different working frequencies

Size of patch	4x4 cm^2
Resonant Frequency	255 Hz
Load Impedance	0.9 MΩ
Max. V_{pp}	2.5 V
Max. Power	6944 nW

Table 1: Power generated by SATURN at 100 dB and 250 Hz sound frequency

4. SELF-SUSTAINING COMPUTATIONAL SYSTEM DESIGN

To use SATURN in a practical application, it needs to be embedded in a self-sustaining computational system. In this section we look at three different ways of building such system using SATURN. The first system leverages SATURN as a self-sustaining microphone to transfer a wide-spectrum audio sounds (e.g., speech or taps). The second and the third system demonstrate how we can leverage SATURN as a sound energy harvester to build a self-sustaining event detection systems for loud sounds. These self-sustaining wireless sensing and communication systems maintain the form factor of the computational material while being still being potentially cheap to manufacture.

4.1 Analog backscatter based communication for sound and vibration

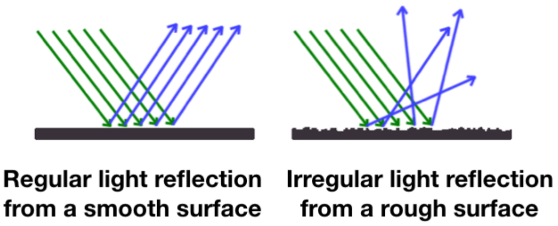


Figure 9: RF analog backscatter can be explained using an analogy to the modulation of intensity and angle of reflection of light from a rough surface

We combine the self-sustaining mechanical vibration sensing property of SATURN with a self-sustaining communication technique called analog backscatter to build a thin flexible material tag which can self-sustainably both sense and communicate audio. The word backscatter in analog backscatter means reflection. We can explain analog backscatter by using a simple analogy of reflection of light rays (Figure 9). When light hits a mirror, it bounces off the surface at an angle equal to the angle of the incoming light wave. However, when light hits an irregular surface it gets diffused, resulting in modulation in both the intensity and angle of reflection of the light waves. Analysis of the received diffused light can help deconstruct the shape of the irregular surface from which it is reflected. Similar to the light waves, when radio frequency (RF) waves are incident on a specially designed tag, they get modulated in amplitude and phase. This reflected RF from the tag can be processed at the receiver to extract information of the phenomenon which caused the modulation. In our tag design, the modulation is due to voltage generated in SATURN resulting from sound or mechanical vibration (Figure 10).

5.png

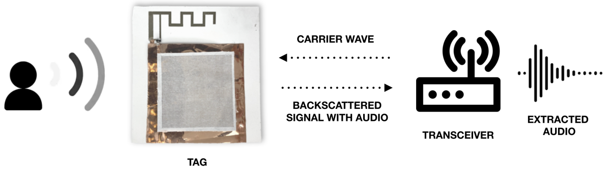


Figure 10: Self-sustaining sound sensing and communication architecture using SATURN and analog backscatter technique

Our prototype tag consists of SATURN, a junction gate field-effect transistor (JFET) which acts as a voltage-controlled impedance device, and a printed antenna (Figure 11) [1]. Sounds and vibrations in the environment result in generation of voltage in SATURN which in turn changes the impedance in the circuit via the JFET. This change in impedance changes the radar cross-section of the antenna resulting in amplitude modulation of the incoming RF waves. Our tag is an example of a computational material for audio and vibration sensing and communication. The simple circuit design of our tag maintains the thin, flexible form factor of SATURN and can easily be embedded in everyday objects and surfaces.

Amplitude modulation based analog backscatter does not allow for unique IDs for different SATURN patches, but other methods like Frequency Shift Keying (FSK) [11] can allow for this capability by the addition of a sub-hundred microwatt power energy harvesting method based on easily available sources like wireless energy or light sources in the room.

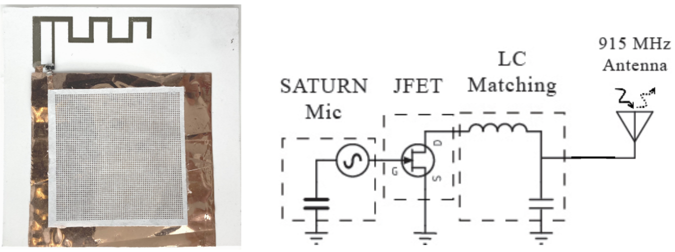


Figure 11: Tag consisting of simple circuitry – SATURN sensor connected to printed antenna using a JFET and an impedance matching circuit

4.2 Flip-bit data storage and RF interrogation system

The 6.9 μW of power generated by SATURN due to a loud sound can be used to flip a bit in non-volatile memory to record the occurence. Considering the maximum power transfer theorem (Jacobi's law), the usable power we can obtain is approximately 50%. Thus, we might harvest up to 3.4 μJ/sec. The energy required to program a "1" into NAND flash memory is 2 μJ [8]. Given that the sounds we wish to monitor will probably last for several seconds, there is more than enough power to record the acoustic event. Going further, SRAM bits can be flipped at approximately 10-100 pW of power [5, 10], suggesting that rudimentary computation might be performed to determine if the flash memory bit should be written. Recorded bits might be read later using a passive RFID interrogation system, which can both read the recorded state and reset it.

4.3 Ultra-low power radio communication system

SATURN could power longer range radio transmitters allowing real-time alerts to sounds that exceed a loudness threshold. Talla et al. [13] have recently demonstrated a 915 MHz analog LoRa backscatter communications device that can communicate at greater than 11 bits/sec while hundreds of meters away from its RF source and receiving antenna. While their system currently uses a battery, their theoretical IC design consumes only 9.25 μW of power. With sound events lasting on the order of seconds, one can imagine a SATURN-based system storing power until it has enough to enable a 915 MHz backscatter transmission to the receiving antenna, announcing the event. As long as the event continues to occur, the SATURN system can transmit alerts every few seconds to a remote monitoring station. In this manner, acoustic environmental monitoring can be performed without the cost and environmental difficulties of batteries.

5. APPLICATION SCENARIOS

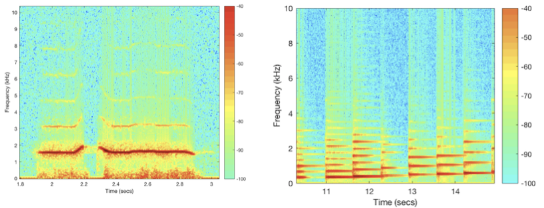
In this section we explore how self-sustaining computational systems based on SATURN can be used in everyday scenarios.

5.1 Ubiquitous microphone for interaction and control

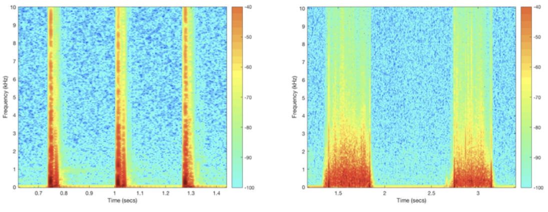
Figure 12: SATURN is flexible and can be made in different shapes and sizes, allowing instrumentation of everyday objects such as a soda bottle, shirt, and paper crafts.

The thin and flexible form factor of SATURN allows it to be placed on many different surfaces (Figure 12). SATURN patches might be placed on walls or lamp shades in the home to act as a baby monitor or extend the range of audio input for home assistants (e.g., Amazon Echo or Google Home). In addition to audio sensing, SATURN can be used as a vibration sensor to detect simple input tap touch to control objects. For example, imagine a SATURN patch in the form factor of a post-it note which could be placed on walls or tables as a wireless light switch.

5.2 Audio sensing post-it notes for infrastructure mapping and authentication



Whistle **Music instrument notes**



Taps **Blows**

Figure 13: Examples of sounds sensed by SATURN

Imagine placing a SATURN post-it note at a conference room door entrance which only authorised users can open using a password consisting of unique combinations of blow, whistle or tap (Figure 13). In a public restroom scenario SATURN post-it notes can be placed on restroom doors; a special sequence of tapping can start a maintenance request. Multiple SATURN patches with pre-mapped IDs can be placed at multiple places in a nursing home and could be used for easy access to an emergency help button by tapping or speaking to the patch. The main advantage of such audible post-it notes is that they are cheap and disposable, reducing concerns of them being lost or stolen.

5.3 Context sensing and localisation

Using multiple SATURN patches can allow beam-forming such that individual voices may be better isolated acoustically. For example, placing several SATURN patches on a conference table can help localize a speaker to improve speech quality (Figure 14). Outdoor arrays of SATURN patches patches might sense loud sounds like a gunshot and transmit the sound to indoor transceivers for real-time triangulation (Figure 15).

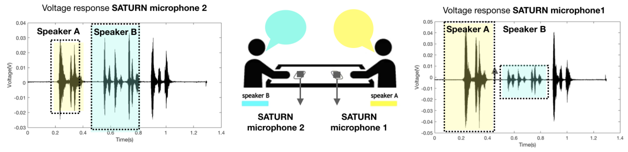


Figure 14: Multiple SATURN patches placed on a table can localize speakers

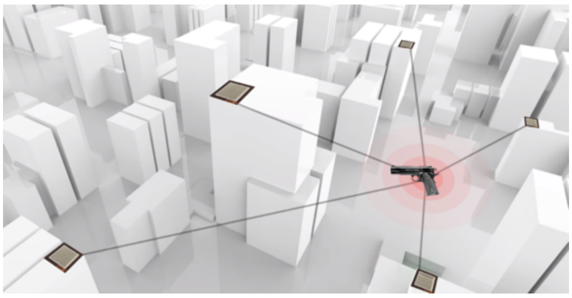


Figure 15: Outdoor SATURN patches can sense and communicate gunshot sounds to indoor transceivers for real-time triangulation

5.4 Industrial and home monitoring

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. Arranging SATURN patches in an array [2] increases the range of audio sensing to almost 10 meters allowing monitoring of large rooms. Thus, a SATURN array can be used as a remote glass-break detector for security systems in office buildings.

5.5 Ambient monitoring of noise pollution

Imagine an airport located in the center of a city, like San Jose International in California, that would like to monitor its acoustic environment so as to not exceed safe noise levels for its employees and to keep overly loud aircraft noise footprints within airport boundaries (Figure 16). A SATURN-based system can be tiled on various buildings and at various distances on the runway. As planes take off, they generate loud sounds due to engines, fans and air turbulence. The peak in the sound spectrum generated by aircraft is near the 200-300 Hz band (Figure 45 in Khorrami et al. [6]) with decibel levels reaching 105 dB_{SPL} at 5 m. These values are consistent with the resonant frequency of the SATURN patch and would result in generation of power $> 6.9\ \mu$W accumulated over different frequency bands. This power could be used to communicate the event by either of the two self-sustaining systems described above in Section 4.2 and 4.3.

Other work zones that might monitor for sound thresholds exceeding human hearing tolerance include construction zones, mines, music venues, power stations, airports, spaceports, and military environments. Similarly, SATURN-based sensors might be used for monitoring catastrophic events such as landslides, avalanches, polar ice calving, mine cave-ins and mine gas explosions.

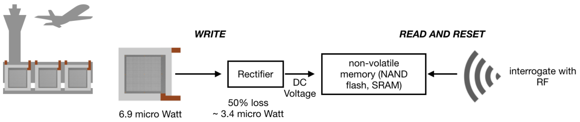


Figure 16: Recording a loud acoustic event using power generated from a SATURN microphone

5.6 Localisation of tanks in war zones

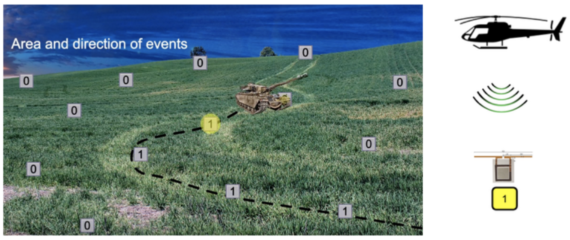


Figure 17: Dropping remotely interrogable SATURN sensors to monitor tanks and ordinance in a war zone

In a more futuristic application, the United Nations might drop SATURN-based sensors from an airplane into a conflict zone. The sensors would monitor the acoustic and ground vibration environment for the movement of tanks, heavy chemical transports, mortars or exploding ordinance. As tanks go by, the sound flips a bit in the sensor. Later, an official with a reading device might sweep the field to interrogate the sensors. In a more extreme scenario, a low flying drone aircraft might sweep a strong RF signal over the region and record which sensors report hearing an event. The pattern of reporting sensors can reveal the direction of travel of a vehicle and point to possible hiding areas for that equipment, providing proof for treaty violations.

6. EMERGING RESEARCH THEMES

Work on SATURN suggests several research directions for computational materials in the future. We describe some of those themes here.

6.1 Self-sustaining sensing opportunities

There are many other opportunities for designing self-sustaining sensors based on different energy harvesting phenomena and for placing them in the context of self-sustaining computational systems. SATURN is just one example; we can design many other TENG-based self-powered sensors in different form factors for varied applications. A photodiode or solar cell can be re-cast as a self-sustaining motion sensor whose rate of wireless transmission is directly coupled to the amount of light to which the sensor is exposed. Another example is to re-think batteries, which generate power due to an electrochemical reaction, as sensors. Design changes to the cathode, anode and electrolyte can make the cell relatively inert until exposed to a catalyst such as air, water or other chemicals, thus making the cell a self-powered sensor for detecting (and communicating) the presence of the chemical catalyst. A third opportunity regards thermoelectric harvesters, which generate energy due to heat flow and temperature gradients. Imagine a steam pipe constructed out of the dissimilar metals typically used for thermoelectric generators. When steam flows through the pipe, the temperature difference would cause energy to be generated which would power the wireless transmission of packets. The higher the temperature difference, the more power and the higher the rate of packet transmissions.

6.2 Transitioning from devices to materials

While such self-sustaining sensors can be made as individual macro units, current technology trends support a lower level integration of the sensing into the material itself. Advancements in printed and flexible electronics are enabling the production of self-sustaining sensors in thin and flexible form factors that can be conveniently added to current materials. New research in flexible antennas, transistors and integrated circuits [9] demonstrates how simple computation and communication can be added while maintaining flexibility and low cost. Finally, with radio backscatter technology and applications improving rapidly [11, 20], a surprisingly low amount of energy needs to be generated locally for communication to the external infrastructure.

6.3 Rethinking traditional semiconductor manufacturing techniques

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 post-it note sized 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. When SATURN is placed in a self-sustaining computational scenario, the cost is driven higher, depending on the active transistor component being used. This expense suggests reexamining the manufacturing process such that it can be more efficiently scaled. How should the traditional semiconductor industry best support large-scale ubiquitous sensing? How can we change traditional manufacturing techniques to be able to support applications where objects and surfaces have computation embedded in it.

6.4 Designing the user experience

Computational materials promise to further blur the divide between the physical and digital worlds, opening a very interesting set of research challenges for HCI and design practitioners. How do we design user experiences around this new technology? What tools and design frameworks can be adapted for an Internet of Materials? When the form factor of computing is more like the objects we use in crafting, how does that change the way we think about designing user experiences. Indeed, as the playful art object in Figure 12 suggests, computation that looks more like paper or other material inspires more creative uses by those familiar with those materials. And computation that looks and feels more like everyday objects will change the way 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.

6.5 In-material privacy frameworks

One of the biggest challenges and opportunities with ubiquitous computing systems is designing for privacy [7, 19]. Privacy-aware designs often focus on both technological and social approaches [7, 12]. What new approaches will the Internet of Materials era inspire? What privacy models will need changing? One opportunity comes in the form of the privacy principles of choice and consent and proximity and locality [7]. Computational materials focus on local sensing, which may provide users a natural mental model of their range of operation. For example, SATURN microphone patches could be constructed at a physical level to require tapping with a finger 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 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. A SATURN patch for monitoring an industrial machine might only listen to certain low-pitched hums, outside normal speech ranges, that indicate upcoming failures. Similarly, a glass-break detector might be tuned for high pitches outside of human hearing ranges. It is our hope that by focusing on embedding "privacy in the material structure" as a first-class research priority, we will also find ways of improving the function of the device along the often-related dimensions of power usage, networking and user interface.

6.6 Building a community of multi-disciplinary researchers

Building SATURN involves solving technical, system level and design challenges which span many fields. 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. Creating devices for an Internet of Materials needs researchers who can adopt an aggressively multi-disciplinary mindset to collaborate and learn the language of many different fields.

7. CONCLUSION

SATURN is an initial example of a computational material. It senses vibration and can convey that information wirelessly without batteries or wired power sources. Its simple multilayer construction resembles an everyday material; it looks and feels like paper, yet it behaves like a wireless microphone. The multidisciplinary, out-of-the-box thinking that resulted in SATURN's creation and application is meant to inspire a new direction for computing. Using power (requiring no external power source), cost (large-scale manufacturing with simple materials), and form factor (looking more like an everyday object) as driving factors leads to a rethinking of ubiquitous computing that can drive the community forward for the coming decades in the same way that Weiser's vision propelled us for the past few decades.

8. ACKNOWLEDGMENTS

We would like to thank our collaborators at Georgia Tech's Nanotechnology Lab—Prof. Zhong Lin Wang, Yi-Cheng Wang, Steven L. Zhang and Zhengjun Wang—for their work and guidance on the original version of the SATURN paper [3]. We thank Diego Osorio and Fereshteh Shahmiri for their help in making diagrams for the original SATURN paper, some of which have been adopted in this review article. We thank Mohit Gupta for the device vibration simulations, and we are grateful to Jin Yu and Hyunjoo Oh for their help in making the teaser image for this paper.

9. REFERENCES

[1] N. Arora and G. D. Abowd. ZEUSSS: Zero Energy Ubiquitous Sound Sensing Surface Leveraging Triboelectric Nanogenerator and Analog Backscatter Communication. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*, pages 81–83. ACM, 2018.

[2] N. Arora, Q. Xue, D. Bansal, P. McAughan, R. Bahr, D. Osorio, X. Ma, A. P. Sample, T. E. Starner, and G. D. Abowd. Surface++: a Scalable and Self-sustainable Wireless Sound Sensing Surface. In *Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services*, pages 543–544. ACM, 2019.

[3] N. Arora, S. L. Zhang, F. Shahmiri, D. Osorio, Y.-C. Wang, M. Gupta, Z. Wang, T. Starner, Z. L. Wang, and G. D. Abowd. SATURN: A Thin and Flexible Self-powered Microphone Leveraging Triboelectric Nanogenerator. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(2):60, 2018.

[4] L. Galbrun and K. Kitapci. Speech Intelligibility of English, Polish, Arabic and Mandarin under Different Room acoustic conditions. *Applied Acoustics*, 114:79–91, 2016.

[5] N. Gilbert, Y. Zhang, J. Dinh, B. Calhoun, and S. Hollmer. A 0.6 v 8 pJ/write Non-volatile CBRAM Macro Embedded in a Body Sensor Node for Ultra Low Energy Applications. In *VLSI Circuits (VLSIC), 2013 Symposium on*, pages 204–205. IEEE, 2013.

[6] M. R. Khorrami, E. Fares, and D. Casalino. Towards Full Aircraft Airframe Noise Prediction: Lattice Boltzmann Simulations. In *20th AIAA/CEAS Aeroacoustics Conference*, page 2481, 2014.

[7] M. Langheinrich. Privacy by Design—Principles of Privacy-Aware Ubiquitous Systems. In *International Conference on Ubiquitous Computing*, pages 273–291. Springer, 2001.

[8] V. Mohan, T. Bunker, L. Grupp, S. Gurumurthi, M. R. Stan, and S. Swanson. Modeling Power Consumption of NAND Flash Memories using Flashpower. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 32(7):1031–1044, 2013.

[9] K. Myny. The Development of Flexible Integrated Circuits based on Thin-film Transistors. *Nature Electronics*, 1(1):30–39, 2018.

[10] P. Raikwal, V. Neema, and A. Verma. High Speed 8t SRAM Cell Design with improved Read Stability at 180nm Technology. In *Electronics, Communication and Aerospace Technology (ICECA), 2017 International conference of*, volume 2, pages 563–568. IEEE, 2017.

[11] V. Ranganathan, S. Gupta, J. Lester, J. R. Smith, and D. Tan. RF Bandaid: A Fully-analog and Passive Wireless Interface for Wearable Sensors. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(2):79, 2018.

[12] N. M. Richards. The Dangers of Surveillance. *Harvard Law Review*, 126(7):1934–1965, 2013.

[13] V. Talla, M. Hessar, B. Kellogg, A. Najafi, J. R. Smith, and S. Gollakota. LoRa Backscatter: Enabling the Vision of Ubiquitous Connectivity. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 1(3):105, 2017.

[14] Z. L. Wang. Triboelectric Nanogenerators as New Energy Technology and Self-powered Sensors–Principles, Problems and Perspectives. *Faraday discussions*, 176:447–458, 2015.

[15] Z. L. Wang. On Maxwell's Displacement Current for Energy and Sensors: the Origin of Nanogenerators. *Materials Today*, 20(2):74 – 82, 2017.

[16] Z. L. Wang, J. Chen, and L. Lin. Progress in Triboelectric Nanogenerators as a New Energy Technology and Self-powered Sensors. *Energy & Environmental Science*, 8(8):2250–2282, 2015.

[17] Z. L. Wang and A. C. Wang. Triboelectric Nanogenerator for Self-Powered Flexible Electronics and Internet of Things. In *Meeting Abstracts*, number 26, pages 1533–1533. The Electrochemical Society, 2018.

[18] M. Weiser. The Computer for the 21st Century. *Scientific American*, 265(3):94–105, 1991.

[19] M. Weiser. Some Computer Science issues in Ubiquitous Computing. *Communications of the ACM*, 36(7):75–84, 1993.

[20] Y. Zhang, Y. Iravantchi, H. Jin, S. Kumar, and C. Harrison. Sozu: Self-Powered Radio Tags for Building-Scale Activity Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 973–985. ACM, 2019.

[21] H. Zou, Y. Zhang, L. Guo, P. Wang, X. He, G. Dai, H. Zheng, C. Chen, A. C. Wang, C. Xu, et al. Quantifying the Triboelectric Series. *Nature communications*, 10(1):1427, 2019.