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Technical Perspective
The Future of Large-Scale Embedded Sensing

By Joseph A. Paradiso

THE DREAM OF computational material has been in the air for decades, dating at least to the Smart Matter program at Xerox PARC in the late 1990s. Inspired by the complexity of biological skin, my own team (see *Sensate Media*, *Communications*, Mar. 2005, p. 70) and others have looked to integrate distributed sensing into large flexible membranes, a trend that continues in research today (see the *IEEE 2019 Proceedings on Flexible Electronic Skin*). Most of these devices, however, are actively powered. The SATURN system described in the following paper works passively, energized essentially by static electricity generated as layers move relative to each other during vibration, hearkening perhaps to, at a smaller scale, electret microphones, which exploit charge trapped on their foil membrane to produce a vibration-dependent voltage. Using only two components—an FET and matching inductor—the authors are able to modulate the resonance of a RF antenna that can be embedded in the material and read out via passive backscatter from an external transmitter, allowing a material to work as an audio pickup without a power source.

Traditional work in this area has tended to exploit piezoelectric polymers like PVDF, which generate voltage under strain. Triboelectrics present a different approach, although provide probably an even higher source impedance that would challenge power conversion even more. SATURN sidesteps this entirely, using the generated voltage directly at the gate of the resonance-modulating FET (ironic, in that we usually work to avoid destructive static charge there—but the potentials are much lower here). Hence, the key contribution of this paper is a means of transmitting audio features from a passive triboelectric-generating material.

Remotely monitoring audio from backscatter in passive structures has a long and notorious history in electronic espionage—classic stories abound of ingenious Russian bugs built into resonant structures all over the U.S. Embassy in Moscow from over a half-century ago—microwave backscatter from cavities with a flexible surface could pick up audio across the complex (see Eric Haseltine's *The Spy in Moscow Station*, for example, Leon Theremin, famous for his free-gesture electronic musical instrument from circa 1920, is purported to be the inventor of these devices). But as this paper attests, it's back in vogue again—some recent incarnations of passive acoustic sensor backscatter can also be found in the recent work of Josh Smith's team at UW (for example, his batteryless cellphone) and my colleague Fadel Afib's self-powered underwater sonar backscatter sensor, which is acoustically interrogated instead of using radio.

The authors espouse the vision of large surface-area passive sensors that can be cheaply manufactured, perhaps by a roll-roll process, and laminated onto the walls and surfaces in our environment. There is potential competition here, however, from the opposite tack—making the sensors small and compact using MEMS and standard IC technology and embedding them into the smart surface like raisins in pudding. Looking at the application proposed here, for example, Jon Bernstein and his team at Draper Lab have recently built a passive MEMS acoustic switch that closes at a particular sonic amplitude—this could easily toggle a backscatter antenna to enable remote readout. The world also begins to see implementations of 'Smart Dust' as envisioned by Kris Pister in 2001—for example, compact stacks of bare IC die, sparsely powered by photodetectors on the top layer and talking via backscatter, such as prototyped by a University of Michigan consortium.

How we will power these sensors is an area of similar technical tension. When the power requirement is sufficiently low to warrant energy scavenging, a small, embedded battery will generally survive close its shelf life, which can approach the product life cycle of the embedded sensors and provide a more economical and practical energy solution. On the other hand, if we have a multitude of devices in our environments that must last decades, energy harvesting may be mandated, and here we will need area for photovoltaics, thermoelectrics, piezoelectrics, or even, as in this case, perhaps triboelectrics or maybe RF or inductive energy receivers. Large flat sheets provide such area, and researchers have built systems using all of these approaches (see 'The Superpowers of Super-Thin Materials,' *NYT* Jan. 7, 2020), even building sensors and electronics into fibers and fabrics, but it's not yet clear what the driving applications are. We will see flexible display 'wallpaper' in the not too distant future, but this will definitely be a powered system (this world will witness an interesting tension between photons beamed to our retinas via ubiquitous AR glasses vs light from everywhere displays). Perhaps its first market will be in building materials (for example, passively detecting dampness, strain, or temperature, after they are installed, as envisioned in my team's original 'Sensor Tape' project from 2012).

Passive sensate structures, as espoused in this paper, will enable sensing everywhere. We are already living in a world where networked sensing risks privacy behind every door—once our commonplace materials beam new streams of ubiquitous sensor data, this reaches another level, as even coarse but plentiful data can leverage potentially invasive contextual determination. The paper describes some simple ideas of physically 'opting in' with these materials, but I think the details of how privacy will be managed will be much more complex when life is enveloped with so many digital peepholes looking at us from everything. **C**

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