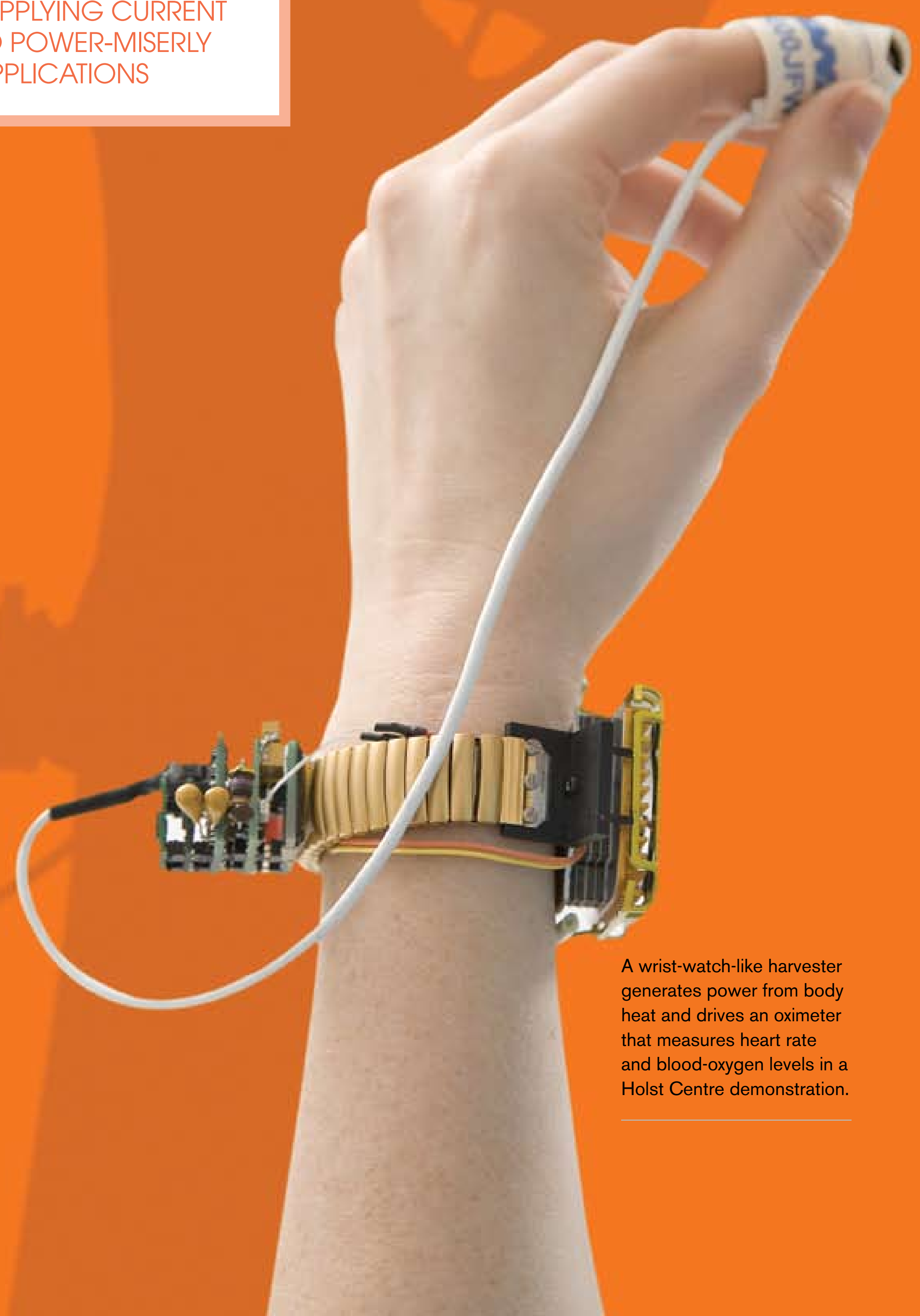
THERMAL, VIBRATION, AND RF SOURCES SHOW POTENTIAL IN SUPPLYING CURRENT TO POWER-MISERLY APPLICATIONS



A wrist-watch-like harvester generates power from body heat and drives an oximeter that measures heart rate and blood-oxygen levels in a Holst Centre demonstration.

BY MAURY WRIGHT • EDITOR IN CHIEF

HARVESTERS GATHER ENERGY FROM THE ETHER, POWER LIGHTWEIGHT SYSTEMS

There's no free lunch, right? Your mom and dad probably told you as much. So surely we can't extract energy from thin air. Or can we? Actually, the human body, factory machines, radios of various types, and many other things emit energy in the form of heat, vibration, or RF waves. And it's looking increasingly plausible that designers can devise systems that scavenge the stray energy and convert it for use in powering systems—albeit very low-power ones. You won't soon see a mobile handset powered from the ether, but potential realistic applications include portable medical monitors and even home-automation devices.

Energy harvesting or scavenging is more about enabling compelling new applications than about saving money on power. Tech-industry visionaries have for some time been speaking of an era of ubiquitous processors embedded into the fabric of our lives. Borrowing a passage from our 50th anniversary issue (www.edn.com/50th), Texas Instruments Principal Fellow Gene Frantz said, "You can almost say that we are on the path to the vanishing product—where the product will be so small and insignificant in size, but so significant in capability, that we really don't know where we have it; we just know we have it." It's easy to imagine many such microprocessor-based devices both on our persons and in places such as a smart light switch or thermostat.

Arguably, microcontrollers have already pervaded our lives. Microchip Chief Executive Officer Steve Sanghi states, "You get up, and the first thing you interface with is an alarm clock, then maybe an electric shaver, a hair dryer, a blender, a refrigerator. … By the time you have left your home, you have used a large number of microcontrollers already. Then you get into your car, and there are 40 to 50 microcontrollers adding to your safety, comfort, convenience, and entertainment." Sanghi points out that microcontrollers monitor highway traffic and that, at work, we face another avalanche of the devices.

Today, an ac source or batteries can conveniently power all of these applications. The next step, however, in which processors are embedded in textiles, in walls, on bridges, and everywhere, will require either a replacement for the battery or at least a symbiotic technology that can charge a battery from the ether, greatly extend the usable life of a battery, or do both. The answer may be the energy harvesters that this article discusses or perhaps new types of miniature fueled generators (see **sidebar** "Is that an engine on your chip?" in the Web version of this article at www.edn.com/061215df2).

As TI's Frantz is quick to point out, harvesting energy isn't new. Solar energy is an example that has been around for years. Franz points out the long history of solar-powered watches and calculators at TI. Those products use a battery that's augmented with solar panels that recharge the battery. Seiko also briefly sold a wristwatch that was powered by body heat (www.sii.co.jp/info/eg/thermic_main.html).

And there are several examples of enabling technologies that manufacturers are now shipping that designers can use in some manner to harvest energy. You can find previous coverage of the technology and some product examples in **Reference 1**. That article, for instance, covered two products from EnOcean that enable products for home- or building-automation applications.

For instance, EnOcean offers a switch that finds use mainly in lighting control, although you could also use it to control powered draperies, fans, or other devices for which you might have a wall switch in a home or office. The baseline product is the ECO 100 module, which the company refers to as an "electrodynamic" harvester. The company bases the module on a coil and a magnet that together convert linear motion into power. More specifically, the action of a person pushing the switch generates a burst of energy, because the actuator changes the flux through the coil. The company previously offered a piezoelectric harvester for the same application but claims that the new design is more efficient.

EnOcean bundles the ECO 100 into the PTM 200 switch module. The company is selling the product into lighting and other applications. When you depress the light switch, the harvester generates sufficient energy to awaken a processor and radio in the PTM 200 that then transmit three short duplicate message packets to a receiver. You could integrate the receiver into a light fixture, but you would more typically wire it between the ac power and a fixture. The wall switch requires neither wiring nor a battery. The receiver operates from ac power.

EnOcean Vice President of Sales and Marketing Jim O'Callaghan claims that, unlike most other attempts at lighting control, the harvester approach makes economic sense despite a switch design that's far more complex than the typical wall switch, which directly switches the ac power. O'Callaghan claims that the money you save by not running ac wiring to switches will pay for the higher cost of the switch and the receiver that's integrated in the fixture.

According to O'Callaghan, the PTM 200 sells for $10 to $20, depending on volume, and the finished light switch goes for around $50 (one). You can buy the switches for home use from companies such as Ad Hoc Electronics (www.adhocelectronics.com). Ad Hoc's Web site prices the combination of a switch and a receiver module that integrates a relay to switch ac power at about $120 in small quantities. O'Callaghan claims that EnOcean has sold as many as 3000 to 4000 switches into single commercial installations.

Technically, you could argue that the switch product from EnOcean isn't a true harvester, because it doesn't gather stray energy. But it does accomplish the mission of something from nothing. The company has also developed solar and thermal products. **Reference 1** discusses in detail the solar product, which has found use in thermostats inside buildings. The product can harvest incandescent and fluorescent light sources and has two types of energy storage that allow for operation even when the lights are off for extended periods.

Manufacturers of thermal harvesters take advantage of the Seebeck Effect—the ability of a thermocouple to generate power based on the temperature differential between hot and cold plates. EnOcean demonstrated its thermal harvester at last month's Electronica trade show in Munich, Germany. The demonstrations were relatively simple. In one demo, a person placing a finger on a plate would generate the temperature differential needed to awaken the processor, which would then transmit a temperature reading to a receiver con-

AT A GLANCE

- Heat, vibrations, and RF are all potential sources that harvesters can convert into microwatt-power levels.
- Harvesters typically store energy for sporadic use, and designs must couple them to low-power systems that can operate sporadically.
- Designs typically couple energy-harvesting advancements with applications that can take advantage of a sporadic low-power source.

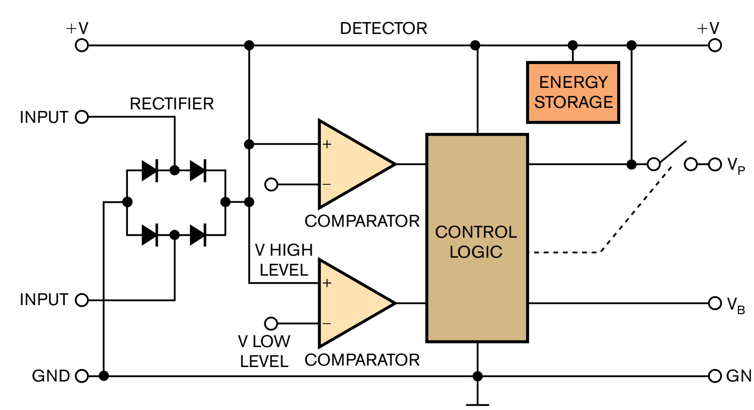


Figure 1 Most harvesting applications rely on electronics that sporadically come to life, but a monitoring subsystem, such as this one, must continuously operate at ultralow-power levels, monitoring the energy store and awakening the processor to the task at hand when sufficient power is available.

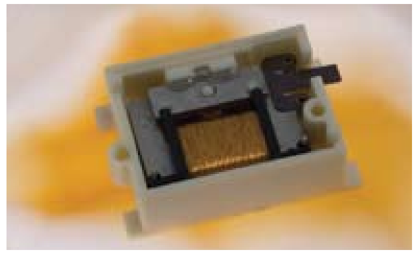
nected to a notebook PC. The second demonstration relied on the difference between the air temperature and the temperature of liquid in a glass to generate power.

The EnOcean thermal harvester, however, is a good example of some of the obstacles in the energy-harvesting market. EnOcean is in the business of designing enabling technologies. It is seeking partners that have ideas for compelling end applications to drive the technology to market. For now, the thermal harvester is awaiting such partners.

Of course, more efficient and lower cost harvesting technology is perhaps the biggest roadblock to broad deployment. A number of universities and R&D organizations are attacking the problem from various directions. The Holst Centre in Eindhoven, the Netherlands, is perhaps moving the fastest on energy-harvesting technology. The research giant IMEC (Interuniversity Microelectronics Center, Leuven, Belgium) together with the Dutch research institute TNO (The Netherlands Organization) established the Holst Centre in 2005. The Wireless Autonomous Transducer Solutions initiative at Holst is a major program that includes energy harvesting. The Holst Centre is working on thermal, vibration, and RF approaches.

Given IMEC's deep involvement in semiconductor and MEMS (microelectical-mechanical-systems) technologies, it's not surprising that the energy-harvesting work seeks to take advantage of those strengths. In the thermal area, the researchers at Holst have focused on a MEMS-based thermopile approach to creating a TEG (thermo-electric generator). A thermopile is essentially an array of thermocouple elements. Electrically, the elements connect in series so that the thermopile sums the voltage that each element produces. The elements connect in parallel, thermally tying together cold or reference junctions and connecting the opposing hot junctions. The greater the difference in temperature across the thermopile, the more current it generates.

As you might expect, commercially available thermopiles are too expensive to meet the needs of a scavenging application that would require many elements in series to generate a usable voltage. But Holst officials believe that the institute can use a MEMS approach to build an acceptable array. Even with the MEMS approach, the miniature dimensions of semiconductors introduce problems, as well. The minute height of the thermocouples essentially allows parasitic plate-to-plate thermal conductance. The Holst researchers hope to address that problem by building the thermocouple array on a silicon rim that both increases the space and provides an isolating air gap between the plates.



The force generated by a person pushing a switch creates the linear motion necessary for a coil and a magnet to generate a power pulse. This pulse can briefly power a processor and radio in EnOcean's wall switch.

The Holst researchers have been working on a prototype application while developing the MEMS TEG. The prototype is an oximeter—a medical device that measures heart rate and the amount of oxygen in the blood. The prototype relies on a commercial fingertip sensor that similar medical applications use. It couples to an electronic subsystem that operates at low power.

Holst has yet to manufacture a workable monolithic TEG. The prototype uses discrete thermopiles manufactured in BiTe (bismuth telluride) with a total of 5000 thermocouple elements measuring 5 to 6 cm^2 in area. The thermopiles mount onto what looks like a wrist watch, placing the reference thermal plate against the skin. Human-skin temperature is typically 33°C. The Holst researchers position the watchlike TEG on the inside of the wrist on the radial artery to maximize the temperature.

In an environment with an ambient temperature of 22°C, the prototype TEG can deliver 100 μW of power. The oximeter design can take a measurement and wirelessly transmit that measurement once every 15 sec while consuming 62 μW of power.

The first step in developing the monolithic TEG is an SiGe (silicon-germanium) device to prove the concept, although the models that the researchers have developed make it clear that SiGe won't deliver anything near the 100 μW of the prototype. They hope to achieve 5 μW with the SiGe TEG implementation. At that power level, you could still run the oximeter, albeit at a much lower duty cycle. Program Director Bert Gyselinckx suggests that the system might take a few measurements per hour rather than four per minute. It's also worth noting that the Hoslt harvester would be a significant advancement over Seiko's thermoelectric watch, which ran from a 1-μW harvester.

Assuming that the SiGe TEG works as planned, the team will then build a monolithic MEMS-based TEG in BiTe. According to Gyselinckx, models show that such a design could deliver 30 μW. Both of the planned monolithic designs will yield a 1-cm^2 die, which is the footprint of the TEG. Although a BiTe TEG isn't theoretically more difficult to fabricate than an SiGe TEG, the SiGe device is manufacturable on many CMOS fab lines, whereas the BiTe device is not. And, although the entire TEG effort shows great promise, a mass-market TEG is surely several years away.

Meanwhile, the Holst researchers are pursuing several other applications and types of harvesters. Gyselinckx believes there will be other medical applications in hearing aids and perhaps even in medical devices that you implant in the body. "There are some thermal gradients inside the body," he says.

Gyselinckx also points out potential applications in industrial and factory settings. A designer looking to deploy a thermal harvester in a factory would likely find usable thermal gradients. But why use a harvester where power is plentiful? Gyselinckx claims that it is simpler to add monitoring networks with no new wires for power or data, which leads to the combination of harvesters and wireless networks.

As for other harvesting technologies, Holst is pursuing both piezoelectric- and electrostatic-based vibration harvesters. In both instances, the researchers are focusing on semiconductor-manufacturing techniques to implement the harvesters. In an electrostatic approach, the researchers hope to use MEMS technology and multiple wafers. One wafer will move with respect to the bottom fixed one in the face of vibration and, in doing so, vary capacitance to generate current to a load.

You will also find vibration-based harvesting technology from Perpetuum. **Reference 1** covers the basics, and, more recently, *EDN* covered the company's newest generator (**Reference 2**).

Of course, the researchers at Holst, EnOcean, and other companies also face the problem of low-power circuits and power-miserly wireless-network technologies. That's one reason that Holst built an end application. Check the Holst Web site for details on the dc/dc-converter design and other specifics of the oximeter.

Likewise, much of EnOcean's work is on the system-level details, such as the wireless network. The company chose to locate its wireless network in the 868.3-MHz band, in which it can do short data bursts using amplitude modulation and do so in compliance with regulatory agencies worldwide. The company claims that, with 50 μW of power, the technology can transmit a signal over a range of 300m.

The need for ultralow-power ICs and components is yet another problem that designers will face in harvesting applications. ALD (Advanced Linear Devices) has for years tended a niche market in very-low-power MOSFETs and now hopes to use that expertise in harvesting applications. The company first announced what it calls zero-threshold MOSFETs, which operate with a gate threshold as low as 200 mV. Later, the company introduced programmable arrays of such MOSFETs and now plans a series of modules for energy harvesting that leverage the low-power MOSFETs.

According to ALD Chief Executive Officer Bob Chao, much of the secret to getting harvesters to work in real applications is in monitoring the stored energy and controlling just when the processor and other circuitry can awaken and perform the task at hand. The simple schematic in **Figure 1** indicates Chao's point. You must have some circuit that operates continuously to monitor the harvester store, and that's where ALD's technology comes into play.

Chao claims that ALD will introduce three modules in early 2007 for use in vibration applications. What he is calling Model A for now will be a 4.5-mJ device that can deliver 25 mA at 1.8V.

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The device will sporadically deliver this load—perhaps once every few hours, depending on the vibration environment. The power capacity will be suitable to temporarily power a Zigbee application. The other modules will offer even greater power but perhaps with less frequent operating capacity. Chao claims that the modules will be the size of AA batteries.

Chao also claims that ALD has deployed its technology in a series of vibration-powered sensors on an automotive bridge. The passing autos create the vibration. But Chao can't name the installation for now, because ALD simply supplied the enabling technology to the contractor.

Although much of the energy-harvesting technology is in the prototype stage today, it's clear that some real application will emerge in the ensuing years. Other players include Thermo Life, which is working on thermal harvesters. Both MicroStrain and Ferro Solutions are working on vibration-based harvesters for military applications. The challenge to designers will be to match a harvesting technology to a compelling application. **EDN**

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IS THAT AN ENGINE ON YOUR CHIP?

On the one hand, battery developers have made great strides in developing improved battery chemistries that extend battery life, result in smaller batteries, and improve recharging. On the other hand, experts relate that batteries still don't offer good energy density relative to their size and weight. So, research continues into alternatives, such as fuel cells and even miniature fueled engines.

EDN and many other publications have over the years covered fuel-cell technology for applications ranging from powering notebook PCs and mobile handsets to autos and homes. *EDN* published its last major story on the topic two years ago (Reference A), and there's been limited real-world success in fuel cells for the most part since that article appeared.

More recently, micro fuel cells have entered the picture. A micro fuel cell is essentially a fuel cell built in a semiconductor structure using MEMS (microelectrical-mechanical-systems) technology. But *EDN* this year reported that such micro fuel cells weren't likely to see use in mainstream applications such as handsets (Reference B).

But this article on energy harvesting focuses on the kind of niche applications that could potentially benefit from some type of miniature engine that you construct using a MEMS process.

DARPA (Defense Advanced Research Projects Agency) is pushing such research, albeit initially mainly for military applications. The agency notes that the energy density of hydrocarbon fuels is at least 50 to 100 times better than the energy density of the best lithium-ion batteries (Reference C).

Meanwhile, researchers at the Microsystems Technology Laboratories at the Massachusetts Institute of Technology are working to construct a true gas-turbine engine inside a chip. Again, MEMS technology is the key, and the driver is initially the military (Reference D). The researchers hope to have a working prototype this year.

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