Energy harvesting

New materials and systems glean untapped microsources and megasources to power minisensors, electronics, remote surveillance equipment and even soldiers

by Wendy Hankle

In January 2006, a group of researchers, businessmen and suppliers got together in Dallas, Texas, to discuss an old field with an emerging potential: energy harvesting. The topic of the day didn't center on rolling plains dotted with windmills or huge arrays of solar panels – but innovative ideas to make the most out of ambient energy on a more diverse scale. Think shakable flashlights. Crank-powered computers.

Today, a National Science Foundation grant and six conferences later, the Center for Energy Harvesting Materials and Systems is up and running, a formal structure making official the efforts of the 2006 workshop participants. CEHMS has grown over the years, binding together its members in an effort to understand and realize the true potential of a surging field. CEHMS is a direct result of the NSF's formation of Industry/University Collaborative Research Centers. There are 30 such centers in the nation, each a collaborative effort between academia and industry.

The field is a little deceptive. Although it might be instinctive to chalk up the current interest in the energy harvesting to a new, consumer-driven focus on green technologies, CEHMS associate director Shashank Priya thinks that's barking up the wrong tree. "If you look at the actual business data, this isn't driven by green engineering. It's mainly driven by the need to replace batteries, replace wires and enhance the portability of devices."

"The growth in energy harvesting has been very dramatic," Priya continues. "The market has basically spread out in many different domains: automobiles, buildings, roads, waterflows, human body networks, sensors and portable devices."

But booms often yield busts, especially in a field where the sky may seem the limit – and no idea may seem too far out.

"Some things are a flash in the pan, and some go on to become a mature technology," says Dan Inman, CEHMS director. "My biggest complaint about my colleagues who are working in this area is that most people tend to overstate it. [They say,] 'I designed this energy harvester and it's going to change the world.' It's not."

While some in the field may be tempted to bite off more than they can chew when estimating an idea's potential, there are technologies and applications of energy harvesting that should be watched. Applications in monitoring the health of architectural structures, for instance, or applications to harness the full potential of piezoelectric materials – and even ocean waves – may not provide a pathway to earth-shattering breakthroughs, but they can facilitate incremental changes to the current way we use energy. They also provide some guideposts to figure out how we can make energy harvesting benefit our infrastructure, our health and our society.

Energy harvesting to be showcased at EMA conference

The upcoming Electronic Materials and Applications conference, Jan 20–22, 2010, in Orlando, Fla., will feature several symposia that address energy-harvesting research and challenges. For example, several of the individuals interviewed for this article are involved with the symposium, "Energy Harvesting and Sensors for Structural Health Monitoring." For more information on the conference, go to page 55, or visit www.ceramics.com/ema2010. ■

Structural health monitoring

On Aug. 1, 2007, an eight-lane, steel-truss arch bridge collapsed in Minneapolis, Minn., during rush hour, killing 13 people and injuring 145. The bridge carried about 140,000 vehicles a day, and was the state's fifth busiest. Eventually, the cause of the collapse was narrowed down to design flaw complicated by additional weight on the bridge at the time of the accident.

Embedded sensor systems, powered by energy-harvesting materials, can monitor bridge stresses such as those that led to the 2007 bridge collapse in Minneapolis, Minn., and trigger warnings before they occur.

The catastrophic failure of such a devastating magnitude is what researchers, who are exploring the potential of energy harvesting as a way to affect structural health monitoring, are trying to prevent. SHM investigators believe that sensors can be manufactured and affixed to – or in – structures like bridges and roadways. Then data on tension, strain, vibration, temperature, fatigue and corrosion can be recorded and transmitted.

SHM provides a huge application area for energy harvesting, particularly in the area of exploiting piezoelectrics. Thomas Daue is president of a company called Smart Material, located in Sarasota, Fla. The firm develops and manufactures piezocomposite materials that combine the piezoelectric properties of ceramics with plastic.

"The area with the biggest potential for greatness for our materials is structural health monitoring," Daue says. "There are many different methods, but the difference now is that you can manufacture a device that lasts for a very long time."

SHM monitoring on a large scale requires several nodes, or sensors, for measurement. Powering up the nodes with batteries is limiting in terms of time, lifespan and maintenance. But, with piezo technology, batteries are taken out of the equation. Cost efficiency, however, is not.

Although Daue's piezocomposites have a leg up on traditional PZT materials in terms of longer life, an energy harvester based on piezocomposite material is still three times more expensive than batteries. It's a cost–benefit analysis when determining when to ditch the battery. Daue says if you can

(Credit: Smart Materials.)

Smart Material's Thomas Daue demonstrates a flexible piezocomposite material that can be used to monitor the integrity of bridges, buildings and other structures.

guarantee performance beyond six or seven years and, preferably, up to 20, then such a device makes a lot of sense.

These new applications of piezoelectrics come courtesy of advances in electronics. Vibration-based applications are a traditional role for piezos. In fact, low-power electronics (with a consumption of less than 1 watt) has been a major application area for vibration-based energy harvesting devices using piezoceramics for a long time.

"Energy harvesting from PZT has been known for more than half a century and never took off, and will never take off using the old ideas," Daue argues. "But having a confluence of low-power electronics, which wasn't feasible five years ago – that makes a new product group available for the monitoring of structures. There is a real potential in this very small niche where you can build reliable long-life health-monitoring units."

In addition to piezoelectric materials, CEHMS' Priya says Virginia Tech University has a small-scale windmill technology that produces power in the 1–10-watt range – just small enough to do surveillance or monitoring of bridge or highway health. But, again, cost limits commercialization, and bridge monitoring is no different. It's an application that already has a constrained potential: Priya quickly points out the limited quantities of bridges in the country.

SHM also has important applications with composite materials, for instance, in aerospace applications, Daue says. Unlike aluminum, which can dent, the composites used for aircraft don't register visual clues and cues about their integrity. Seeding the bodies of planes with wireless sensor nodes that map delamination is one way to keep tabs on the aircraft's structural health, Daue says.

In fact, researchers at the Fraunhofer Institute in Bremen, German, are working on "intelligent" or "smart parts." These are light metal parts embedded with electrical components and sensors during the casting stage of manufacturing. Although details of the process or the materials are not being released, the organization has successfully tested methods and materials.The institute has, for example, imbedded piezosensors in metallic bicycle cranks that relay power production information for competitive cyclists. Light-emitting diodes, batteries, thermocouples and rf identification tags also have been embedded into aluminum, magnesium and zinc, researchers from Fraunhofer say.

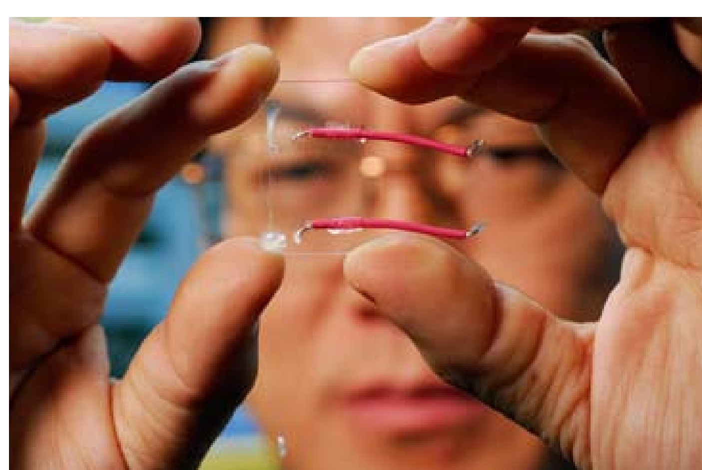
Defense uses

The military's effort to expand the boundaries of "what's possible" is a familiar scenario in R&D, and energy harvesting is no different. Many applications of energy-harvesting technologies are being explored by the military, some as straightforward as finding ways to eliminate the amount of batteries soldiers need in the field. Others take a cue from SHM, using the piezoelectrics to keep equipment in good shape. Any way you slice it, the defense industry has huge power requirements.

"The average soldier carries some ridiculous amount of batteries," CEHMS' Inman says. "To keep those guys going, they have to go out with huge numbers of batteries which eventually have to be exchanged for new ones."

An application developed by researchers at Georgia Technical University has the potential to replace the batteries soldiers carry with something a bit more palatable: a shirt. A microfiber–nanowire hybrid system has been demonstrated to generate electricity by converting physical motion. This could have implications for how soldiers are able to power small electronic devices. The nanaogenerators use zinc oxide nanostructures, which have piezoelectric and semiconducting properties.

In keeping with the potential of



(Credit: Georgia Tech)

Georgia Tech Regents Professor Zhong Lin Wang holds a prototype microfiber nanogenerator composed of two fibers that rub together to produce a small electrical current. Many pairs of these fibers could be woven into a garment to produce a "power shirt."

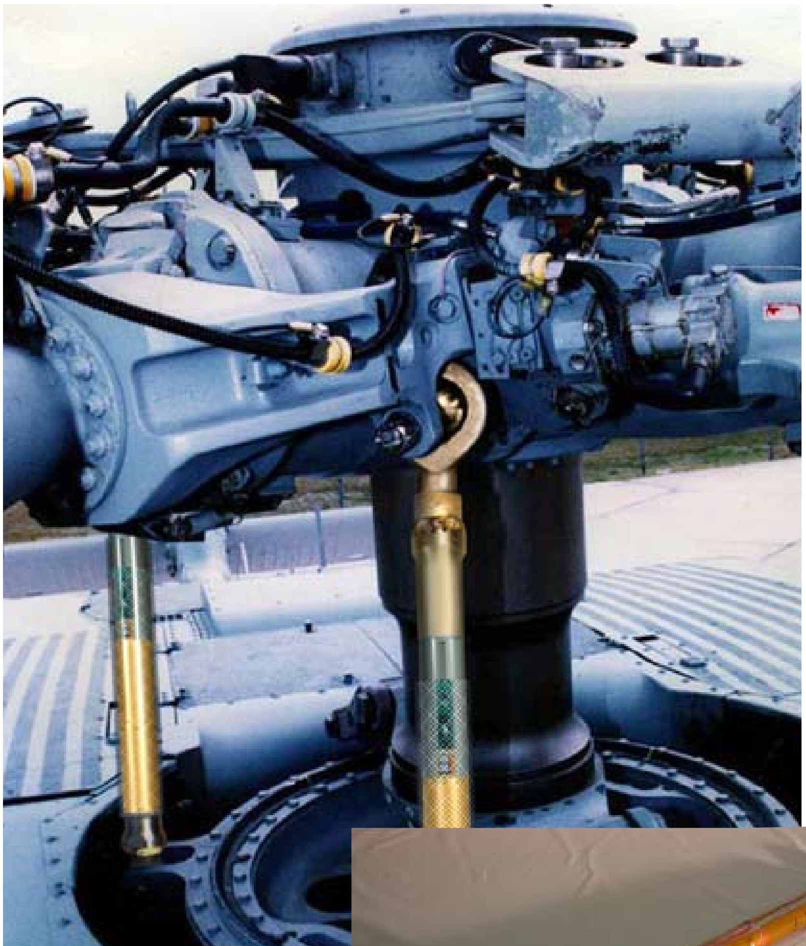
sensing technologies to avert catastrophe on the roadways, applications exist to avert catastrophe by air. MicroStrain, a company in Williston, Vt., is tapping into the power contained in a helicopter's rotating parts. MicroStrain has developed a wireless sensor device that is affixed directly to the pitch link of a Sikorsky H-60 Blackhawk helicopter. It is joined on the pitch link by a piezoelectric energy harvester, data storage device and an rf antenna to transmit the data collected.

There are about 80 fatigue-sensitive areas on the helicopter, says Steve Arms, MicroStrain's president. "They're all expensive and they fatigue," Arms adds. "They tend to be replaced conservatively. If we know the rate at which they fatigue, it will save a lot of money."

The piezo component is a piezocomposite made by Daue's Smart Material and licensed by NASA. "Helicopters are vibrating themselves to death," Daue says. But MicroStrain's application is taking the vibration and strain caused by the blade flapping and converting it into power. The gear box, Arms says, is also a potential site for harvesting by tuning the device to be resonant at the predominant frequency of the gearbox.

"We've received strong funding from Navy, and the application that has been really driving it is the vertical lift helicopter," Arms says. "There's a lot of need in that area and a lot of vibration. It's kind of a sweet spot for this technology."

The Air Force is also sponsoring exploration in this area, working with Virginia Tech to harness the energy created by the vibrations that appear at the tips of the wings of unmanned planes. Collecting this energy potentially starts down the path of self-charging batteries. Researchers are exploring a "broadband" energy harvester, using piezoelectric materials to capture vibrations at a wider range of frequencies. This would mean an increase in open-circuit voltage amplitude, and, therefore, an increase in the power amplitude.



(Credit: MicroStrain Inc.)

MicroStrain's harvestor–sensor system takes its power from the cyclical strains of the same helicopter pitch link that it monitors for fatigue.

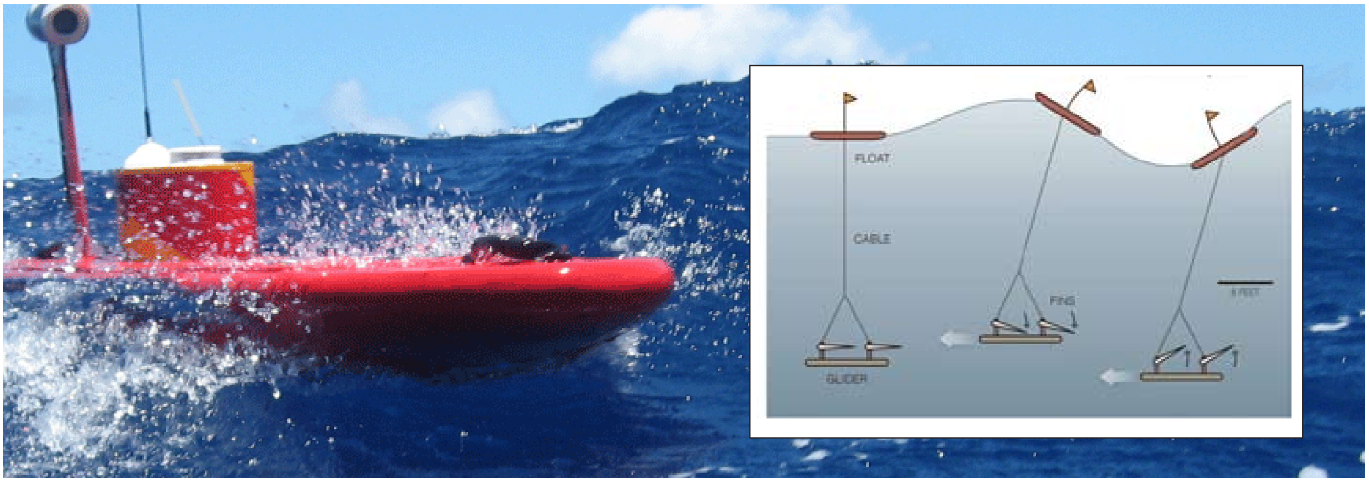
Human health monitoring

CEHMS' Priya points to another type of health monitoring that energy harvesting can help facilitate: human health monitoring. "This is a medically driven area of research, and it's growing," Priya says. Again, piezoelectric materials come into play.

Sensors can be embedded in beds, sofas and, for example, in a room such as the kitchen, to determine the frequency of activity by measuring how many times a particular transducer is stressed. Data collection can include how many times an individual stepped on a particular area and how much time was spent lying on a bed or sofa. Baselines are established to determine the normal activity level, and then new data generated is compared with the baseline.

Priya says the health-related applications are endless. "For the elderly person who doesn't want to use a nurse, but rather wants to use an automated doctor's line, let's say there's a computer connected to a telephone. As software records that there is a problem with that person, that is when someone can be sent to help them," he says.

Priya also points to work done in the lab creating humanoid robotics. The goal is to provide humanlike services to the impaired. "Personal typing assistance, converting speech to text, writing emails, the list of possibilities is endless," Priya says. "Ambient energy can be harvested from sunlight and thermoelectric gradients."



Liquid Robotic's Wave Gliders are autonomous, customizable surveillance platforms. Solar cells on the surface of the vessel power sensors and a below-the-surface wing converts wave motion into thrust.

Out there

More than three-quarters of the world is covered in water with an average depth of two-plus miles. Oceans are one of the most vast and untapped potentials for energy harvesting. Applications range from powering unmanned vessels to climate monitoring and environmental health.

"The energy and size of the ocean is so large, you can stretch out the size of a harvester to accommodate it," Priya says. "The problem has always been a dollar-per-watt number. Compared with solar farms and wind farms, the dollar amount of (wave-energy harvesting) comes out very high."

But that doesn't mean work isn't being done to tap into the potential. A company out of Palo Alto, Calif., Liquid Robotics, has commercialized what it calls Wave Glider technology, This is a two-part system. One part uses solar panels and batteries to support a wide variety of sensor systems. The other part uses a submerged wing apparatus to convert wave motion into thrust. Liquid Robotics officials say Wave Gliders can travel far and patrol large regions without refueling.

Along similar lines, the Defense Advanced Research Projects Agency has demonstrated wave-powered autonomous buoys. One of the buoys, a vertical heave harvester, is estimated to be able to produce more than 10 watts of power. DARPA also is investigating wearable motion-energy harvesters, capable of producing between 200 milliwatts and 300 milliwatts at 1 hertz movement.

Another application comes in the form of "artificial muscle" developed by researchers at SRI International. The device is a polymer-based system, developed as an alternative to electric motors, that expands and contracts when a voltage is applied to it. Interestingly, it can also generate electricity when stretched.

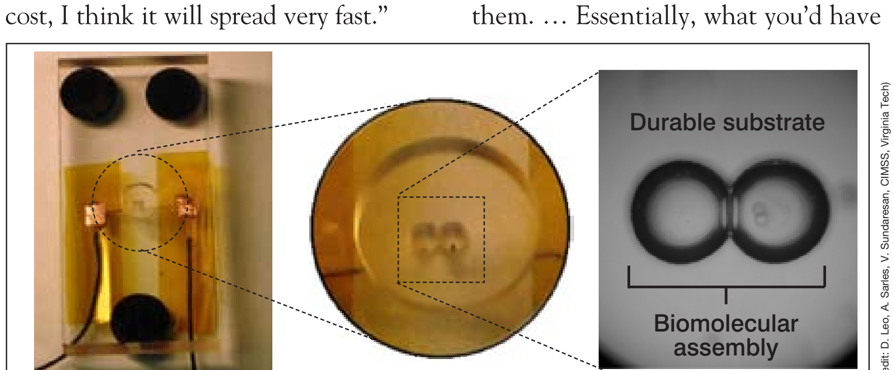
The material is attached to a buoy, and energy is harvested as the buoy bobs up and down in the water. The material is thin and pliable, and can be rolled. The buoy-muscle system has been field tested off the coasts of Florida and California. The long-term goal is to have a system that will feed electricity to the buoy – or a power grid on land.

"[Ocean-wave energy harvesting] is an area where research is ongoing," Priya adds. "As soon as we can bring down cost, I think it will spread very fast."

For Arms, looking to the future means looking to the past. "Radio technology is going through a tremendous transformation right now," he says. "New radios coming on the market that leverage ultra-wide-band technology use 10 times less power when they transmit, but transmit 20 times faster. Consumers are using 200 times less energy getting data, and that means harvesters are going to get smaller, costs are going to go down.

"We see a really exciting opportunity here," Arms says.

One of the more creative, forward-thinking applications of energy harvesting technology comes from the lab of Don Leo, a researcher at Virginia Tech. Leo is exploring the potential of harvesting energy from bilayer membranes that mimic cell walls. "We can create these [membranes] inside synthetic materials, inside plastics," Leo says. "When we do that, we can incorporate many of the same biomolecules into them. … Essentially, what you'd have



Virginia Tech researchers have created tiny batteries using cell wall-like membrances.

would be a biological battery."

The mechanism for harvesting the energy comes from a concentration gradient across the membrane, incorporating proteins to pass the current in the gradient. Another method from Leo's lab uses an enzyme, ATPase, which converts ATP into a current.

Admittedly, these technologies are several years from the market, but Leo sees encouragement. "The amount of power we've been able to get per unit area is fairly competitive. It's on the order of a solar cell using indoor light," Leo says. "For a first cut, that's not bad."

Leo and others have worked over the past year to develop more-robust platforms, for instance, a film with a durable exterior that could be picked up, moved and shipped, just like any other material. And, because the materials used are biological in nature, in-vivo energy harvesting applications are on the horizon.

"The major innovation here is that we're trying to really perform the energy conversion in a way that is inspired by and mimics biological systems," Leo says.

Back to the basics

On a very basic level, energy harvesters show the most promise in simply reducing energy requirements, augmenting current power sources, and providing a way to cut the number of batteries and wires required in current technologies.

"Our focus is on devices that normally would be battery operated. Transmitters, radio receivers and the like," Smart Material's Daue says. "[These are] things that would normally require a little battery, nothing major. But now we can build a fully autonomous device where there's a vibration present, and it can be maintenance free for several years."

In addition to piezo-type products, MicroStrain's Arms sees thermal-energy harvesters as an important area of interest and research. Low voltage coming through a thermoelectric generator can be converted into usable power, with the application driving the thermopile size. "An application of this can be a turbine engine with airflow," Arms says. "Find something with a nice thermal gradient or heat flux. You don't need a lot. You can do a lot with a 5°C–10°C gradient."

In fact, researchers at Fraunhofer IPM say they have an experimental application that draws on that principle. They developed a thermoelectric generator that converts heat from car exhaust fumes into electricity. The thermal gradient uses the temperature difference between the exhaust pipe and the pipe carrying engine cooling fluid. The gradient can be several hundred degrees, according to Fraunhofer IPM. Once the energy is harvested, it is used to support the car's electical functions.

(Credit: Fraunhofer IIS.)

(Credit: Freescale Semiconductor.)

Microgenerators, such as those being developed at Fraunhofer IIS (above), can convert small temperature gradients, even body heat, into current. Freescale Semiconductor's ultra-low-voltage dc-to-dc converter (right) allows solar cells to operate levels as low as 0.32 volts, and, in some cases, as low as 0.25 volts.

Another Fraunhofer group, the Institute for Integrated Circuits, has developed a novel voltage converter that can handle input voltages as low as 20 millivolts. This means that tiny amounts of energy extracted from the environment can be used to power small electrical loads. With a 2°C temperature gradient, the equivalent of the difference between the temperature of human skin and room temperature, for instance, a 2-squared centimeter thermoelectric generator used in connection with the new voltage converter IC can produce up to 4 milliwatts. Fraunhafer says that such small and low-cost voltage converters are available now and will be useful in small appliances, medical and automotive engineering, facility management, automation and logistics.

Each form of energy harvesting has its potential – and its limitations – CEHMS' Inman adds. Piezoelectric methods can change any strain into a current, but challenges remain. Motions tend to be small, and the mechanics of designing the harvester are dependent on the nature of the motion, which is different in almost every application. Electromagnetic methods work better with larger motions and a fair amount of space, but limitations come into play with microfabrication.

However, in October, Sony Corporation announced its development of a wireless power transfer system that eliminates the use of cords and cables over short distances for electronics. Although still far from the scale that Nikola Tesla dreamed of, Sony has found success in this field by the harnessing of magnetic resonance. Using magnetic resonance, electromagnetic energy is sent to other devices that share the exact resonant frequencies. This transfers up to 60 watts of electrical energy for a distance of about 50 centimeters. This technology has vast potential considering the growth of networked electronics – and their corresponding numbers of connector cables.

"Research in energy harvesting is driven at the materials level," Priya says. "Once you have quick materials, then the second part is to design the transducer structure, next the electrical interface needed to take and transfer the data."

To that end, a company called Freescale Semiconductor has developed power conversion technology for photovoltaic applications. The high efficiency, ultralow voltage dc-to-dc converter enables IC startup thresholds to hover around 0.32 volts – an improvement over traditional thresholds of about 0.7 volts. Applications of the new system would allow for harvesters to be designed to recover energy at ultralow voltages.

(Credit: Sony Corp.)

A prototype of Sony's wireless power transfer system.

One of the biggest limitations to energy harvesting technologies and applications doesn't have to do with devices, sensors, biological systems or the great deep ocean. It just might be expectation. "The biggest failing is when companies call me up and say, 'We want you to harvest some energy,' without knowing how much there is available to harvest," CEHMS' Inman explains. "You can't ask somebody to harvest a given amount of energy without knowing very detailed information about what's available." ■