Title

Distributed Energy Harvesting for Energy Neutral Sensor Networks

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Energy Harvesting Projects

EDITOR'S INTRODUCTION

This month's Works in Progress column has four contributions. The first examines how harvesting environmental energy in sensor networks changes the way an application developer views energy management, and discusses prototype devices. The second proposes devices that combine energy harvesting and data acquisition. The third explores novel approaches for optimizing the power extracted using piezoelectric materials. The final one explores kinetic and thermal energy harvesting from human users' activities. *—Anthony D. Joseph*

DISTRIBUTED ENERGY HARVESTING FOR ENERGY-NEUTRAL SENSOR NETWORKS

Aman Kansal and Mani B. Srivastava, *University of California, Los Angeles*

Embedded deployments, such as sensor-actuator networks, constitute a large class of pervasive computing devices. Unlike cell phones or laptops, which users can periodically recharge, pervasive devices must operate on their initial batteries. The highest reported energy densities for current battery technologies range around 3.78 kJ/cm^3, which implies that for a low-power device operating at an average consumption of 1 mW to have a 10-year lifespan, it needs a large 100 cm^3 battery. Thus, energy supply is a major bottle neck for system lifetime, and harvesting energy from the deployment environs can help alleviate this. UCLA's energy harvesting project (http://nesl.ee.ucla.edu/projects/heliomote) is making a two-pronged effort to address the various challenges in building practical energy harvesting sensor networks.

First, we've started developing a theory for energy-neutral systems. These systems strive to meet application performance requirements using only environmentally available energy and can thus sustain themselves infinitely (until the hardware or application becomes outdated). In contrast to battery-operated systems, power management in energy harvesting systems differs fundamentally in that it's the available power that's limited and not the total energy. Also, power availability varies in time and might be different at different nodes in the network. While most applications result in energy consumption at multiple nodes, some flexibility in determining which specific nodes are used is usually possible. For instance, when a sensor network records an event in the environment, there's a choice in determining the exact route used for routing the data to the user. Clearly, the achievable system lifetime depends on how the relay nodes make these choices with respect to the environmental energy's spatio-temporal profile. Notably, the network as a whole must make the task allocation decisions in a distributed manner because no single node has complete knowledge of the entire network's energy opportunity. We developed analytical models for the harvesting and consuming entities and derived theorems that characterize their achievable performance.[1] We also demonstrated distributed protocols to schedule tasks in accordance with the environmental harvesting opportunity available at different network nodes.[2]

The second part of the effort involves developing working prototypes, which has also revealed several interesting issues in the harvesting systems' hardware and software design. Our first prototype consists of a network of solar energy harvesting sensor nodes called *heliomotes*. Each heliomote (shown in Figure 1) consists of a solar energy har-

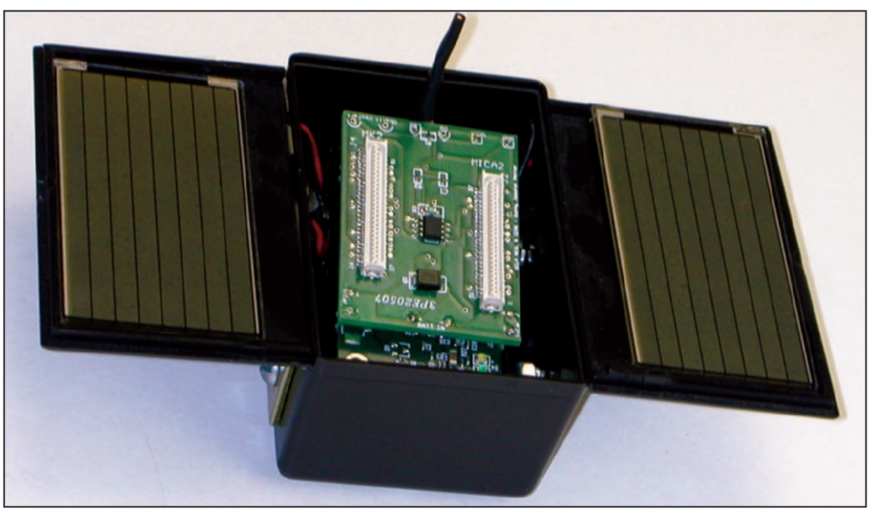

Figure 1. A heliomote, an energy-harvesting sensor node.

vesting circuit, which powers an off-the-shelf sensor node, stores excess energy in a rechargeable battery, and, most significantly, tracks the environmental energy availability. A digital interface provides the tracked energy data to the sensor node and uses it for our harvesting-aware power management strategies. Evaluating such strategies is part of ongoing work, but our initial experiments have revealed that explicitly measuring the environmental energy is crucial to the design.

For more information, contact Aman Kansal at kansal@ee.ucla.edu.

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POWER AND DATA WITH ENERGY HARVESTING TECHNOLOGY

Julian Randall, Thomas von Büren, and Gerhard Tröster, *ETH Zürich*

We usually only use energy harvesting systems to convert and collect the environment's energy flows. A new wearable computing concept is considering these energy flows to be data flows as well. An example of this concept is an automatic (self-winding) watch that uses an inertial energy conversion system both to collect energy and to measure the movement of the user's wrist. Once the system can communicate the latter information to an on-body computer, the user can use the watch as an energy self-sufficient context sensor and avoid buying an accelerometer.

We can generalize the concept of "power and data" across other energy harvesting technologies, including solar and thermoelectric. At ETH Zürich's Wearable Computing Laboratory, we're investigating numerous approaches to validate the concept. In one approach, we use solar modules on the outside of clothes as a very low-resolution camera for rudimentary location tracking. Our simulations and first experimental results indicate that we can satisfactorily measure essential location parameters such as speed and distance from light source with a few solar modules positioned around the shoulder. Investigating appropriate algorithms and hardware will complement this offline analysis to provide real-time location detection and services. This could lead to a practical system in which flexible solar modules would also be a visually attractive smart clothing feature.

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HARVESTING ENERGY FROM PIEZOELECTRIC MATERIAL

Thomas J. Johnson and William W. Clark, *University of Pittsburgh*

Technological advances in the electronics industry during the last decade have made it possible to reduce many electronic devices' size as well as the power they require to operate. This power requirements reduction has created an interest in developing new methods of powering these devices as an alternative to the current disposable battery technology. One possible solution is to develop a device that will convert an ambient energy source into usable power for the devices. We've been researching the development of devices that use piezoelectric materials to convert mechanical energy (from pressure, force, and vibrations) into electricity.

The goal is to create small, lightweight structures that couple very well to mechanical excitation and convert the most useable electrical energy.

Piezoelectric materials have the interesting ability to generate an electrical charge when an applied mechanical load deforms them or, inversely, to exhibit strain under an applied electrical field's influence. It's the former effect that we and many other researchers are seeking to exploit to develop piezoelectric energy harvesters. Many types of piezoelectric materials display the piezoelectric properties. Some are naturally occurring materials, such as quartz, and others have been engineered. We're investigating using lead zirconate titanate (PZT), which exhibits a relatively high conversion of mechanical to electrical energy.

Current piezoelectric energy harvesting research falls into two key areas: developing optimal energy harvesting structures and highly efficient electrical circuits to store the generated charge or present it to the load circuit. Our research focuses primarily on the first area, in which the goal is to create small, lightweight structures that couple very well to mechanical excitation and convert the most useable electrical energy.

Our initial research in energy harvesting structures focused on a unimorph piezoelectric circular plate (a PZT layer bonded to an aluminum substrate) that would be driven by a fluctuating ambient pressure source, such as from a scuba tank or blood pressure. Our research shows that by simply creating the proper electrode pattern on the piezoelectric material (or by poling the material in the correct pattern), which we termed *regrouping* the electrodes, we could produce an order of magnitude increase in available electrical energy.

Because ambient mechanical vibrations are a prevalent energy source in many environments, our work is in developing optimal devices that can convert these vibrations into a usable electrical energy. The focus is on a unimorph piezoelectric cantilever beam that undergoes base excitation. As the beam vibrates, it experiences different stresses along its length. Taking this into account, we can regroup the electrodes to target specific vibration modes, resulting in maximum charge collected (as was the case with the circular plate structure). These types of design optimizations will improve piezoelectric energy harvesting technology's miniaturization and practicality.

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HUMAN PASSIVE POWER

Loreto Mateu and Francesc Moll,
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We can exploit environmental energy harvesting to power electronic circuits in several low-power systems, such as wearable devices or sensor networks. Each application has its own energy harvesting options. In the Universitat Politècnica de Catalunya's Electronic Engineering Dept., the High Performance Integrated Circuits Design Group is focusing on energy harvesting for consumer electronics. Our goal is to calculate the energy we can harvest from a persons' activity. More specifically, we can classify energy harvesting from human activity as active or passive, and we're working to achieve passive power. Active power means that the user is doing a specific work to generate the energy, while passive power uses the user's everyday actions without conscious intervention and therefore causes the user less discomfort.

As we focus on user-generated energy, we examine two types of energy: kinetic and thermal. We consider three types of transducers to convert the kinetic energy into electrical energy: piezoelectric, capacitive, and inductive. Our work has been in modeling the piezoelectric transducer's behavior and studying the optimum mechanical structure. For each energy source, we'll also study optimum power conditioning circuits.

Our next objectives are modeling the human body as a thermal source and studying kinetic energy during normal day activity in different parts of the body.

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