Energy Harvesting and Conservation

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Pervasive computing aims to integrate computation into our daily work practice to enhance our activities without being noticed. In other words, computing becomes truly invisible. Yet at the heart of every pervasive computing system are electronic components that consume energy. Managing the energy needs of mobile systems, or systems for which reliable power isn't guaranteed, can be a significant distraction for users. How can we minimize user involvement in the energy management process to make pervasive computing devices more pervasive?

Power management techniques

Most users can attest—from their experience with mobile phones, portable media recorders, and portable media players—that power management can be distracting. Of course, the magnitude of distraction depends on the specific application, the hardware, and the energy source's characteristics. Researchers are trying to address this issue predominantly by reducing power consumption and developing improved energy sources. Unfortunately, both approaches have limitations.

Reducing power consumption

Attempts to reduce power consumption have focused on hardware that consumes less power and software that judiciously manages power consumption. Advances in VLSI fabrication and the reduction of a transistor's dynamic power consumption have led to dramatic decreases in the power that electronic circuits consume. This in turn has allowed pervasive systems to deliver greater capabilities on a fixed power budget, or similar capabilities on a smaller power budget. However, in the future, it remains unclear to what extent this trend will continue. Static power consumption is becoming a large fraction of total power consumption, because chips will consume more power even when they are idle, yet we know of no long-term technical solution. In addition, as users become more accustomed to the convenience of wireless capabilities and transfer large amounts of data over wireless interfaces, physical laws will dictate the minimum amount of energy that needs to be transmitted. And VLSI circuitry can't overcome these limitations.

Energy-aware software is a compatible technique in which the software is designed to conserve energy where possible. For example, the software might judiciously power-down components not in use, or engage power-saving operating modes when higher-power modes aren't warranted to deliver a lower quality of service. The challenge for such software is to limit the degree to which these optimizations distract users and to limit the amount of user attention and configuration that's needed. This problem is further exacerbated when mobile devices evolve from single-purpose devices to multipurpose computers with operational char-

acteristics similar to those of desktop computers.

Improving energy sources

Today, batteries represent the dominant energy source for systems that can't be readily powered from a household electricity supply or for which power cables haven't been laid—at a remote weather station, for example. Although exponential improvements have occurred in hardware components (for example, in processor speed, memory density, and network bandwidth), such improvements haven't occurred in battery technology, and we don't anticipate any significant changes in the future.

At the same time, owing to shrinking component sizes and the consumer electronics industry's persistent integration of more features and capabilities, our expectations for mobile systems continue to outpace conventional batteries' energy storage capabilities. This trend has given rise to the development of alternative energy-storage solutions, such as direct methanol fuel cells. However, these cells are no panacea because, like batteries, they require user management and hence distract from the application at hand. Moreover, the energy density of batteries in some mobile devices is already very high, and safety concerns arising from rapid accidental discharge would become more serious with significant increases in energy density.

Energy harvesting: A promising new approach

Fortunately, techniques exist that, given the appropriate applications and modes of use, can significantly reduce or simplify user involvement in the energy management process. One such technique is *energy harvesting* (or *energy scavenging*), which aims to collect ambient energy to help power systems, possibly storing energy when it isn't required—typically in batteries, capacitors, or springs.

Many energy transducers exist, each offering differing degrees of usefulness depending on the application. Perhaps the best known transducers are solar cells, which have long been used to power simple hardware components such as calculators, emergency telephones along the highway, and low-grade lighting for pathways at night (charged during the day). Another type of transducer converts the energy contained in a vibrating object into electrical energy—researchers have used these to harvest energy from floors, stairs, and equipment housings.

A third type harvests mechanical energy, such as that produced by a person walking and an object's movement—for example, self-winding watches, which wind themselves from the swing of a person's arm. Hybrid cars that transfer energy from the engine to the battery during braking are a more modern example of this technique, which has been used in commercial vehicles. Yet another type of transducer is one that converts the momentum generated by radioactive reactions into electrical energy. Some transducers can also exploit temperature gradients, or pressure gradients, to produce electrical energy.

Energy harvesting is most applicable to applications that demand small amounts of continuous power or that have short periods of high-power use, which previously harvested and stored energy can provide for. Energy harvesting can also supplement more conventional energy sources—for example, when a mobile computer is in a low-power sleep state or charging its battery. These supplements might offer significant contributions to a computer's energy needs, given a suitable usage pattern. For instance, if a mobile user extensively uses a computer for short periods of time, an energy harvesting system might be able to ensure the battery is always topped up during the standby period when the computer isn't in use.

Although energy harvesting techniques can significantly benefit some systems and their associated applications, they're limited by the efficiency of the transducers and the raw energy available. As we discussed earlier, a complementary technique for extending battery lifetime is to design software that judiciously manages power consumption. *Energy conservation* summarizes the numerous techniques in this area—such as shutting down disk drives after a time-out period or slowing down a processor's clock. Given that the energy contributions of energy harvesting will be modest and will likely be serendipitous depending on the location of use, conservation techniques must be used hand-in-hand with energy harvesting to make best use of its contribution.

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Future trends

The semiconductor industry believes feature sizes for semiconductor devices will continue to decrease for several years, although the rate at which we can build them, owing to significant manufacturing complexity, is slowing. The result will be continued benefits in

In This Issue

The News department's feature story provides a brief survey of the commercial uses of energy harvesting, offering insight into the types of products that are both under development and currently available. It examines energy harvesting in a broader context, considering how it not only can replace batteries but also can reduce energy costs and provide a source of energy when one isn't readily available, such as in underdeveloped regions or disaster situations. It describes products ranging from new VLSI technology and thermoelectrically powered microprocessors to shake flashlights, wind-up solar-powered radios, and solar-powered refrigerators.

The first peer-reviewed article, "Energy Scavenging for Mobile and Wireless Electronics," is also a survey, but it focuses on the amount of energy available from various ambient sources and the technology you can use to harness it. The next article, "Improving Power Output for Vibration-Based Energy Scavengers," provides an in-depth study of how you can harvest energy from mechanical vibration—one of the previously less studied ambient-energy sources.

"Battery-Free Wireless Identification and Sensing" demonstrates how you can further use ultra-high-frequency electromagnetic energy, generated to read RFID tags, to provide a remote-sensing capability. Then, in "Inductive Telemetry of Multiple Sensor Modules," the authors analyze power-induction techniques in the context of powering RF sensor modules.

Looking to novel forms of power, we can view the topic of the next article, "Pervasive Power: A Radioisotope-Powered Piezoelectric Generator," as energy harvesting from low-grade radioactive materials or as a new type of battery technology. The authors show how concepts for a harvesting technology and a battery technology can be blended together.

Finally, we turn our thoughts to energy conservation with "Experiences in Managing Energy with ECOSystem." The authors explain how to effectively integrate energy management into an operating system without individually customizing each application for power efficiency.

Complementing the articles are four Works in Progress contributions. The first reports on ongoing research at UCLA into the challenges of building practical energy harvesting sensor networks. The second reports on ongoing research at ETH Zürich into extracting user-level information from the rate of energy harvesting, such as where the user is located or the orientation of a mobile device. The third, from the University of Pittsburgh, explores using piezoelectric materials to convert mechanical energy (from pressure, force, and vibrations) into electricity. The final WiP, from the Universitat Politècnica de Catalunya, reports on efforts to harvest passive energy from a user's daily activity rather than from a specific action.

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switching power, but with current leakage also beginning to play a significant role. This means that power dissipation relates not only to the switching frequency but also to the area of a chip that's actively connected to supply lines. Consequently, we might have to balance the need for more capable electronic circuits that match user expectations against the power cost of delivering the associated increased integration.

As more VLSI designs are built with power characteristics that lend themselves to low-power operation, the commercial opportunity for energy harvesting will become apparent. This will drive interest in improving existing energy transducers, perhaps with more efficient components, or in searching for fundamentally new materials with improved energy conversion properties. Examples include solar cells with greater than 20 to 30 percent efficiency, perhaps based on nonsilicon solutions, or a better piezoelectric material than the commonly used PZT (lead zirconate titanate).

Better understanding of solid-state physics and refined manufacturing techniques will also play a role in improving efficiency. As demand for the personal computer's processing power continues to increase, demand for improving the quality of the manufacturing process also increases to guarantee the required high yields of silicon chips containing tens of millions of transistors. These improved processes have a secondary beneficial effect for other device types, including those used as energy transducers.

Although energy harvesting isn't a solution for all energy needs, it's a compelling concept that will increasingly enhance or even replace batteries for lower-power applications as low-power circuit design techniques and transducer energy efficiencies improve. (Compare, for example, early battery-powered electronic calculators and the solar-powered products sold now.) If the economics are right, for some types of transducers it might just be a question of applying known material characteristics in novel combinations to improve existing energy harvesting techniques.

Energy harvesting is a nascent technology—currently, we can harvest and use only modest amounts of energy. However, the increasing use of pervasive electronics will give this area more attention as researchers try to overcome the difficulty that arises in managing power for numerous devices. Then, as we build new devices with improved efficiency, the amount of energy we can harvest will increase, and eventually we should be able to deploy these technologies in a wide variety of settings.

We hope you find the articles in this issue (see the related sidebar) interesting and contribute to further advances that lead to widespread use of this technology. ℙ

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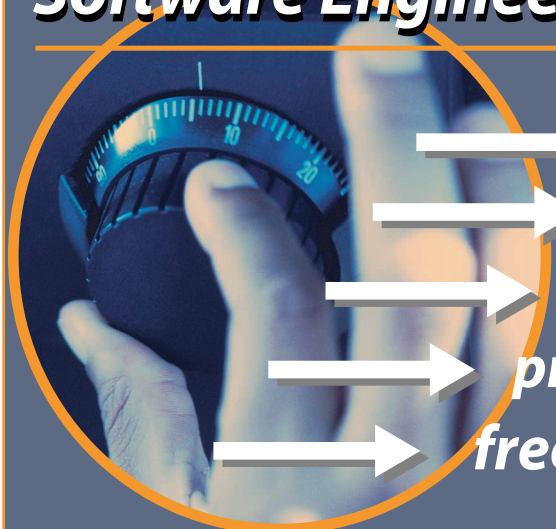
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