Wearable Computers: A New Paradigm in Computer Systems and Their Applications

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THE convergence of a variety of technologies makes possible an entirely new way of using information processing. Continued advances in semiconductor technology produce high performance microprocessors requiring less power and less space. Decades of research in computer science have provided the technology for hands-free computing using speech and gesturing for input. Miniature heads-up displays weighing less than a few ounces have been introduced. Combined with mobile communication technology, it is possible for users to access information anywhere and anytime. Body-worn computers providing hands-free operation offer compelling advantages in many applications.

Wearable computers deal in information rather than programs, becoming tools in the user's environment much like a pencil or a reference book. The wearable computer provides portable access to information. Furthermore, the information can be automatically accumulated by the system as the user interacts with and modifies the environment, thereby eliminating the costly and error-prone process of information acquisition. Much as personal computers allow accountants and bookkeepers to merge their information space with their workspace (i.e., a sheet of paper), wearable computers allow mobile processing and the superposition of information on the users workspace.

When combined with pervasive computing, wearable computers will provide access to the right information at the right place and at the right time. Distractions are even more of a problem when they occur in mobile environments than desktop environments since the user is often preoccupied with walking, driving, or other real-world interactions. A pervasive computing environment that minimizes distraction has to be context aware. Context-aware computing describes the situation where a mobile computer is aware of its user's state and surroundings and modifies its behavior based on this information. A user's context can be quite rich, consisting of attributes such as physical location, physiological state (such as body temperature, heart rate, and skin resistance), emotional state (such as angry, distraught, or calm), personal history, daily behavioral patterns, etc. If a human assistant were given such context, he or she would make decisions in a proactive fashion, anticipating user needs. In making these decisions, the assistant would typically not disturb the user at inopportune moments except in an emergency. The goal is to enable mobile computers to play an analogous role, exploiting context information to significantly reduce demands on human attention. Combined with inferences about users' intentions, context-aware computing would allow improvement in user-perceived network and application performance and reliability. Context-aware intelligent agents can deliver relevant information when a user needs that information. These data make possible many exciting new applications, such as augmented reality, context aware collaboration, wearable assisted living, augmented manufacturing, and maintenance.

Wearable computing brings the power of a pervasive computing environment to a person by placing computing and sensory resources on the user in an unobtrusive way. These computers can be specialized and modular, like items of clothing. Unlike laptops or handheld computers, wearable computers offer many new models to interact beyond keyboards and touch screens, in a natural, intuitive way, such as sound and tactile feedback. Also, wearables can be easily reconfigured to meet specific needs of applications.

Every wearable computer system must be viewed from three different axes: the human, the computer, and the application. Within each of these axes there are difficult problems that must be solved and there are problems that arise from the fact that there are three axes.

The human axis emphasizes wearability, which is defined as the interaction between the human body and the wearable object. Dynamic wearability includes the human body in motion. Design for wearability considers the physical shape of objects and their active relationship with the human form. Researchers explored history and cultures, including topics such as clothing, costumes, protective wearables, and carried devices. These studies of physiology, biomechanics, and movement were codified into guidelines for designing wearable systems. User comfort is a critical design consideration in many applications. New technologies such as smart textiles will significantly improve the functionality and ergonomics of wearable computers. The computer axis deals with the problems related to construction of a system with particular fabrics, size, power consumption, and user interface software. The application axis emphasizes mobile application design challenges and efficient mapping of problem solving capabilities to application requirements. Wearable computers have established their first foothold in several application domains, such as vehicle and aircraft maintenance and manufacturing, inspection procedures, augmented reality, context aware collaboration, language translation, etc.

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The early decades of the 21st century will be a period of excitement and ferment as new hardware technologies converge with research progress on the many essential problems in wearable computing. The fundamental nature of this research and its importance will increase as wearable computing becomes more pervasive. The vision embodied in this research will help us move from a 40-year computing machine preoccupation to a new era of people-centric computing, focusing our technologies increasingly on human needs, augmenting their capabilities and productivity, ushering in an age of distraction-free computing.

We have selected four papers for this special section. The first two papers address the topics of power management and optimization. The first paper, "Nonideal Battery Properties and Their Impact on Software Design for Wearable Computers" by Thomas L. Martin and Daniel P. Siewiorek, summarizes their research on nonideal properties of batteries and how these properties may impact power-performance trade offs in wearable computing. The authors conclude that, when battery behavior is nonideal, the amount of computation completed in a battery life is not increased by lowering the average but by lowering the peak of power or the energy per operation.

The second paper, "Discharge Current Steering for Battery Lifetime Optimizations" by Luca Benini, Davide Bruni, Alberto Macii, Enrico Macii, and Massimo Poncino, proposes multibattery lifetime maximization as a continuous, constrained optimization problem which can be efficiently solved by nonlinear optimizers. The authors show that significant lifetime extensions can be obtained with respect to standard sequential discharge.

The third paper, "Modeling, Analysis, and Self-Management of Electronic Textiles" by Philip Stanley-Marbell, Diana Marculescu, Radu Marculescu, and Pradeep K. Khosla, introduces electronic textiles as new computational fabrics for wearable computers. The paper addresses the modeling of computation, communication, and failure in electronic textiles and investigates the performance of two techniques, code migration and remote execution, for adapting application executing over the hardware substrate to failures in both devices and interconnection links. It is shown that the code migration and remote execution provide feasible methods for adapting applications to take advantage of redundancy in the presence of failures and involve trade offs in communication versus memory requirements in processing elements.

Finally, Bradley Rhodes' short paper, "Using Physical Context for Just-in-Time Information Retrieval," addresses the issue of using intelligent agents to provide the necessary level of usability in wearable computers. The article describes a personal note-taking and note-archival application that automatically displays notes relevant to the current environment to the wearer. While physical context can be used to select useful notes from archives, the subject and text of notes currently being entered are a better indicator of usefulness.

We would like to thank the authors of all submitted papers and the reviewers for their effort and contributions to this special section, which will represent a major milestone in the evolution of wearable computers.

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Guest Editor

Asim Smailagic is a research professor at the Institute for Complex Engineered Systems, College of Engineering, and Department of Electrical and Computer Engineering at Carnegie Mellon University (CMU), Pittsburgh, Pennsylvania. He is also director of the Laboratory for Interactive and Wearable Computer Systems at CMU. This lab has designed and constructed 24 generations of novel mobile/wearable computer systems over the last decade. He has been a program chairman of seven IEEE conferences and program chairman of the Cambridge Conference on High Performance Distributed Computer Systems '89. He has acted as a guest editor and associate editor for leading archival journals, such as the *IEEE Transactions on Mobile Computing*, *IEEE Transactions on VLSI Systems*, *Journal on VLSI Signal Processing*, and the *Journal of Computing and Information Technology* and is one of cofounders of the IEEE Symposium on Wearable Computers. He was a visiting professor at Cambridge University and University of Leeds. He received the Fulbright Postdoctoral Award at Carnegie Mellon in Computer Science in 1988. He was a recipient of the 1992 Tempus European Community Award for scientific cooperation resulting in new curriculum development, the 2000 Allen Newell Award for Research Excellence from Carnegie Mellon's School of Computer Science, recognizing his pioneering contributions to wearable computers, and the 2002 Carnegie Science Award for Excellence. He has written or edited seven books in the areas of computer systems design and prototyping, mobile computers, and VLSI system design. He has made major contributions to several projects that represent milestones in the evolution of advanced computer systems: from CMU's Cm* Multiprocessor System and Edinburgh Multi-Microprocessor Assembly (EMMA) to CMU's current projects on eearable computer systems, smart modules, communicator, and aura pervasive computing. He has served on numerous advisory boards, US National Science Foundation review panels, and consulting assignments, and delivered a number of keynote lectures at international conferences.