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Sensing and effecting environment with extremity-computing devices

Vadim Gerasimov, Ted Selker, and Walter Bender

This paper presents the "extremity" approach to creating user-interface experiences. We describe a class of data-acquisition systems called "extremity-computing devices" and their broad implications to user-interface design scenarios. These devices are used to interface sensors and effectors in wearable-computer applications. Instead of wearing a complete computer, outfitted with interface, storage, and processing components, a user needs only to wear sensors attached to a small microcontroller-based device with rudimentary user interface, local storage, and off-body transfer. Users access data externally, on a device of their choice: hand-held, laptop, or desktop computer, cell phone, etc. We have used extremity devices to gather physiological and motion data, surrounding temperature and lighting conditions, proximity, and the identity of people and objects nearby. We have utilized data gathered by these devices in applications in the areas of education, research, healthcare, and entertainment. The value of the extremity-computing approach for rapid design is shown, as are robust demonstrations of scenarios, including: medical applications for a collaborative exercise game; stress monitoring and feedback; biofeedback training tools; biofeedback controlling toys and game software, teaching people to swing a baseball bat correctly; and helping understand principles of lie detection.

Technological innovation in data recording has a history that long pre-dates the digital revolution, or even the harnessing of electricity. For example, the ratcheting high-tide lines on the ocean shore, that people see daily, gave way to chart recorders, which could record decades of data. In the early 1970s, we saw the emergence of data-acquisition systems that were separate from, but interfaced with, minicomputers. A modular approach still an attractive alternative to designing field equipment. Examples include one-of-a-kind systems, such as the Australian Long Baseline Array telescope facility, and commercially available systems such as PowerLab™ from ADInstruments [1].

As special purpose wearable technology, such as early telemetry systems, gave way to wearable computers, more general-purpose architectures have become the prevailing paradigm [2]. The wearable-computer concept has evolved to include a wearable substitution of all conventional computer components: display, keyboard, mouse, central processing unit, storage, and communication interfaces. However, although wearable computer development has been concurrent with the computer/Internet boom of the 1990s, wearables have not become a mass phenomenon. A possible reason for this is a poor usability of the wearable human-interface components. Wearable displays are bulky and are disappointing in their optical properties. Although the displays may get smaller, their optical properties may never get as good as that of larger displays [3]. The wearable keyboard and mouse substitutes are non-trivial to use. Facile voice I/O remains elusive [4].

A broad research effort has revealed many potentially interesting applications of wearable computers, but it is still hard to point to important reasons to use these computers.

One of the problems is that many applications may work just as well on laptop computers or personal digital assistants (PDAs). Working with a computer usually requires the complete attention of the users. In these circumstances, it may not matter whether the computer is donned, held, sitting on a lap or a desk. However, a wearable computer may perform useful tasks impossible for a conventional computer when wearers do not pay any attention to it. Such tasks include gathering data about the wearers and their surroundings.

There are some exceptions. Systems such as the "body network" created for a scientific expedition to Mt. Everest in 1998 showed that small, special purpose computers allow easy creation of inexpensive systems for high-quality measurement of biometrics in mobile applications. The system consisted of an I^2C network of Microchip PIC microcontrollers. Each of these nodes was attached to a sensor or communication radio in order to transmit information about a climber to a data-acquisition system. The body network is useful and inexpensive example of small interacting programmable devices. The entire system was built in less than six months. The interaction between the devices represented the most of the design complexity.

This paper describes a modular follow-on system to the body network that focuses on data acquisition and aggregation as an architecturally simplifying way of creating ubiquitous computing interfaces. We define a class of devices, which we refer to as extremity-computing devices, and scenarios for these devices that suggest wearing a device or attaching a device to an object is both meaningful and appealing.

Background

Personal electronic monitoring and assistive devices. There are two classes of commercially-successful electronic wearable devices that are not quite computers: (1) Personal electronic assistive devices with a significant user interface, e.g., watches, camcorders, photo cameras, etc; and (2) Personal electronic monitoring devices with little or no user interface, e.g., pacemakers, Holter and event monitors, industrial data acquisition and monitoring systems, sensors that can be surgically installed, thermometers with transmitter that are able to be swallowed, etc.

The assistive devices do not normally perform other useful tasks while the user interface is not engaged. The monitoring devices constantly perform meaningful tasks, but never actively engage in user interaction. There is an emerging class of devices that is somewhere in between these two categories. These devices usually look like a watch, but can display and collect some additional information such as pulse rate or bicycle speed. Devices in this intermediary category are specialized for a narrow set of tasks in a limited set of scenarios.

Devices of both categories rely on autonomous user interface and function independently of a general-purpose computer. Even though some of the devices such as digital cameras have to be regularly interfaced to a computer in order to save information, they rarely use the possibility of user interaction through the computer. For example, it may be much easier and faster to see, set, and fine-tune camera parameters using a computer program instead of a set of buttons on the camera. One of the exceptions is Timex Data Link™ watch [5] that has no usable input interface, but can download schedule, phone book, and other pieces of information from a host computer. Another example of such interaction is synchronization interfaces of PDAs. Although synchronization works both ways, i.e. data goes from the computer to the PDA and from the PDA to the computer, its purpose in many cases is to resolve the user interface deficiency of the PDA by letting the user input and modify information using a regular computer.

There is also a class of experimental devices such as IBM Linux watch [6] or Seiko Ruputer™ watch [7]. These devices are conceived to prove that it is technically possible to run an operating system on a watch. However, they offer very little insight into why a general- purpose operating system may justify the increase in complexity and cost of a watch. Neither of those watches contributes significant ideas to the user interface design or to applications for very small computers.

Interfacing computers with human bodies. Sensory organs of living creatures can often move independently of the body and are capable of reaching out, touching, and feeling the surroundings. Computers, on the other hand, have a very limited set of sensors (if any) confined to a fixed position within the case. Data-acquisition hardware may expand the sensory capabilities and extend the reach of the sensors by a wire length, but still does not offer much mobility to the sensors. Using the biological sensory-extremity metaphor we decided to define a new class of sensor peripheral devices for computers called extremity-computing devices.

The extremity-computing research expands and generalizes the data-acquisition category of wearable devices. First, we make the data-acquisition devices more general or capable of measuring a broad set of signals from a variety of plug-in sensors. Second, we make it easy to transfer real-time and long-term information from those devices to computers. We developed an assortment of research projects that employ devices capable of taking measurement from different sets of sensors and sending this information to computers or other devices for processing and presentation.

Although computers have substantially advanced in their ability to store and process large amounts of data, hardware to gather sensor information is not standard. Data-acquisition devices have been highly specialized and not programmable. General-purpose data-acquisition hardware has usually designed as add-on boards for computers, require extensive wiring, often expensive, and hard to customize.

Many research tasks require some sensor data collection and analysis. Projects related to human interaction, health, environment, physics, and many other areas could be done easier and faster if there were a standard way of developing and attaching sensors to a computer, and standard application-development environment. Education is another area where data collection and analysis is important [8].

Data acquisition boards have gotten small and can be very useful. This paper documents the productivity and scenarios that developing this approach has produced; in particular the approaches ability to allowed to quick development of hardware to collect human-interface sensor data in support of physical human-computer interaction. These systems have been focused on teaching and entertainment applications.

Implementation

HHD device projects. The first device we used to collect and transfer sensor information to the computer was the Handy Board [9]. Although this device had sufficient analog-to-digital conversion and processing capabilities, it was not designed specifically for data collection, which caused several problems. For example, the device was too bulky to wear; it had no wireless-communication capabilities; the on-board memory was very limited; and the serial link required an additional interface board.

Special-purpose integrated computer-sensing systems led to a more stand-alone, miniature device. In 1995, Fred Martin, a researcher in the Epistemology and Learning Group at the Media Lab, worked on a new microcontroller-based robotic-design platform for children called “crickets.” The cricket consists of a small circuit board that fit on the bottom of a plastic 9V battery holder. The crickets seemed like an excellent form factor for the device we needed. We put together a data-collection system consisted of a PIC 16C711 microcontroller, an FM radio-transmitter module, and a power supply circuitry with a 9V battery. The microcontroller provided four 8-bit analog-to-digital converter inputs, additional output pins to control optional LEDs or other components, and processing capabilities to assemble and send data packets over the RF link using a serial protocol. The receiver module was connected to the serial port of a PC or other device, and received power from a keyboard, mouse, or proprietary 5V connector. We call this data-acquisition system HHD device (named after Hand-Held Doctor, the first project to employ the device).

With HHD, the data were broadcast continuously in packets consisted of a predefined header byte, four samples from each analog input, and a check-sum byte. The receiving computer discarded bad packets, which did not cause serious problems, since communication quality was nearly perfect in practical proximity to the computer.

The HHD device was small, light, and inexpensive enough to be attached to wearable objects or embedded in sports gear and toys. It provided a real-time wireless data feed from up to four sensors (Figure 1).

Hand-held doctor for children. The first project that used the HHD device was called Hand-Held Doctor for Children. This project is an example of a wearable application of the HHD board. A computer with an extremity computing device may continuously "feel the forehead" and "keep its finger on the pulse" of a child.

The goal of the project was to help children explore how heart rate, breathing, temperature, and skin conductance changes in different situations [10]. The HHD device, in combination with a set of custom-made sensors, measured and delivered physiological parameters to a computer in real time.

The sensor set included a precision thermistor temperature sensor, a thermistor-based breathing sensor, an infrared optical pulse sensor, and a skin-conductance sensor. Each sensor had an op-amp circuitry powered by the HHD device that filtered, amplified, and shifted the signal to get a desired range and accuracy at the analog-to-digital converter.

The HHD device was attached to a motorcycle helmet (Figure 2) that held the sensors. A helmet is a good form factor for children because it places all the sensors in correct positions requiring little or no adjustment and children are willing to wear a helmet as a toy.

The helmet is able to send data to either a personal computer or a robotic toy. A PC application designed for preschoolers showed an animated cartoon character to visualize pulse, breathing, and temperature in real time (Figure 3). High-school students designed their own robotic toys that responded to the signals received from the helmet. A Lego castle is an example of such a toy (Figure 4). The castle had three motors inside to move a drawbridge with changes in temperature, a flag with breathing, and guards with heartbeat. A Handy board that had a receiver module plugged into the serial port was used to control the motors.

Children also used the HHD device without the helmet in a lie detector workshop. The workshop was devoted to exploration of principles of lie detection based on skin conductance and pulse–two important parameters used in real polygraph tests. The children were very interested in the topic, which allowed them to quickly learn how lie detectors work and why they are not considered reliable.

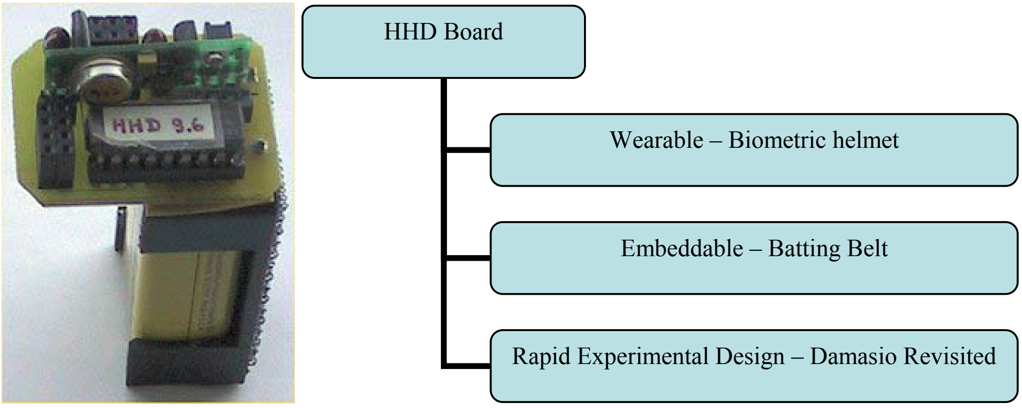

Figure 1 HHD board application diagram

In these projects, the HHD device proved to be a flexible wireless data-acquisition platform for wearable applications. It was compact, inexpensive, and easy to integrate into wearable objects. Using a wireless data-acquisition device allowed us to have advantages of a wearable system in combination with rich user interface and processing capabilities of conventional computers.

The HHD device also allowed children to build their own toys controlled by the Handy Board. The separation of the wearable data-acquisition component from the robotic component helped to build and program the robotic toys faster and without specialized hardware. Since the helmet broadcasted the data, several toys or computers could receive and use the information simultaneously.

This project demonstrates both a change in user experience and a different approach to application design with extremity computing. A child interacts with regular computers or toys that “know” physiological parameters of the child through an extremity device. In the workshops we conducted with children we observed that the wireless interface helps children to feel independent of the object that visualizes the signals. Yet these objects can be perceived as an extension of the child’s body. The small and robust sensor setup makes children more willing to explore and learn how the sensors work. The basic architecture of the HHD board makes it easy to wirelessly connect the biosensor extremity to a serial port of any computer. The sensor interface design of the HHD board also helps to rapidly prototype various body sensors.

Batting belt. From 1996 to 1998, we used the HHD board to rapidly prototype a family of embeddable devices for a baseball bat, the Swings That Think project. If an extremity-computing device is inside a baseball bat the baseball bat becomes a part of the computer; and the computer can sense what the player does with the bat [11].

Figure 2 Helmet with HHD board and sensors

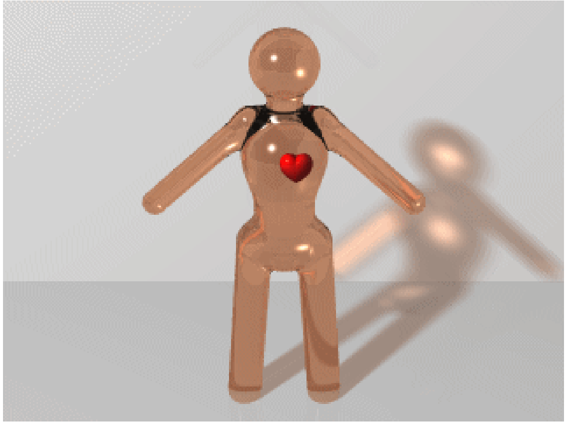

Figure 3 The animation shows pulse, breathing, and temperature.

The goal was to develop a collection of devices that provide real-time motion analysis and audio, tactile, or visual feedback to the user engaged in a task that requires coordination of body movements, and possibly some extra-body affordance, (e.g., a golf club, tennis racket, fishing pole, or baseball bat). The devices performed three functions: sensing, analyzing, and providing feedback to the user. Each device consists of a collection of wearable sensors such as ankle and wrist straps, belts, and hats that sense characteristics of the user's posture and motions as the user engages in various activities.

The focus of the Batting Belt project was to help people hit the ball with the bat. The first prototype of an instrumented bat was based on the Handy board. The sensors consisted of a set of accelerometers and gyroscopes placed inside the bat and on the player's body. The Handy board was placed inside a belt pack and connected to a computer with a cable (Figure 5). Although this system had an adequate data-acquisition support, it was rather heavy, hard to put on, and awkward because of the dangling connection wire. The HHD device allowed us to make a wireless version of the system. Although we had to reduce the number of sensors the system, we nonetheless were able to obtain enough data to provide meaningful feedback. The HHD device was placed on the knob of a hollow aluminum bat and had wired connection to several sensor and indicator LEDs inside the bat (Figure 6).

In this project the HHD device allowed us to design a compact system to acquire and wirelessly deliver information from several sensors to a computer that performed analysis and provided the user with feedback. The light and small wearable component of the system allowed the player to freely move around while the feedback component used a conventional computer to avoid the processing and user-interface shortcomings of smaller computers.

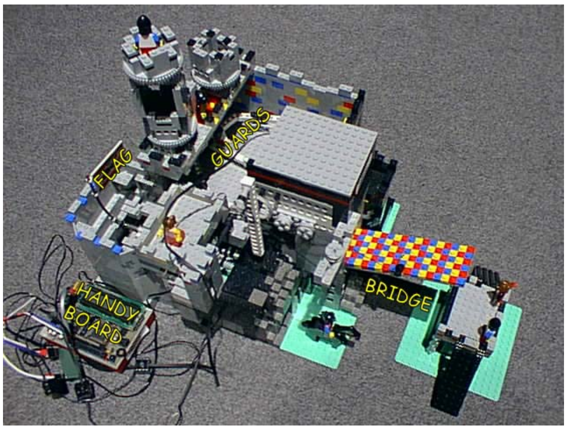

Figure 4 The Lego castle shows pulse, breathing, and temperature.

Figure 5 The Batting Belt

Since the player cannot constantly look at the computer screen during batting practice most of the feedback was provided with sound. The player could listen to the pitch of the background sound that indicated the real-time speed of the bat as well as spoken report after each swing that described possible errors and helped to improve the batting technique. A conventional computer had enough processing capabilities and convenient API to implement such a system.

This project demonstrates how the extremity computing can help in designing systems that help people to learn physical skills in tasks that require advanced coordination of body movement. The HHD board expedited the creation of the bat prototype. Motion sensors we used did not require any additional active components to be plugged into the board. On the software side we implemented the user feedback system on a regular PC and reused the libraries for the hardware interface and basic signal processing from the Hand-Held Doctor for Children project.

The extremity computing approach also defines the user interaction with the system. Instead of looking for a way to implement all user interaction on the bat or in a small proprietary computer, we used user interface capabilities, specifically sound and video output of a regular PC. Making the bat-to- PC connection wireless substantially improves usability of the system by eliminating wires that get in the way when the user moves around.

Damasio revisited. The HHD board was also used in rapid hardware design for an emotional-response experiment. The objective of this Affective Computing class project [12] was to verify results of Damasio's "gambling experiment" that explored the role of emotional response in learning [13]. The HHD board allowed us to rapidly design a system to provide real-time skin-conductance information to a computer game and successfully test with a group of subjects (Figure 7).

Figure 6 Instrumented wireless bat

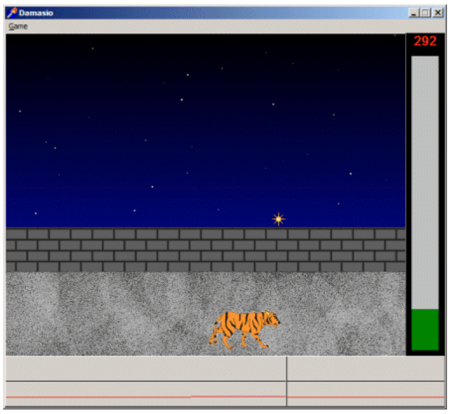

Figure 7 Screenshot of affective game

Employing the extremity computing approach in this project allowed us to build an experimental hardware setup in less than one hour. The HHD board with a single skin conductance sensor wirelessly sent the data to a PC program that processed, stored, and visualized the signal. The PC program engaged the user into interactive process. And the user did not have to be physically connected to the computer.

Hoarder board projects. One of the problems of the HHD device is that the data may be lost when the receiving computer is out of range or the wireless link fails to work because of interference. In many applications that store information for further analysis this is unacceptable. A solution is to add a compact mass-storage device to a data-acquisition system.

To solve this problem we designed a new device called the Hoarder board. Initially developed for the Every Sign of Life project, this device had a CompactFlash card interface and improved data-acquisition capabilities. The system was designed to fit in a belt buckle; it initially included amplifiers for EKG measurement, a one-gigabyte disk drive and radio-frequency communication. Several versions were made.

After discussing the device-design issues with the Wearable Computing group at the Media Lab we decided to add a daughter board and MIThril [14] interfaces to the Hoarder board. Daughter boards with different set of data-gathering features can be independently designed and connected to the Hoarder board. A daughter board gets power and can provide conditioned analog signals to up to eight 10-bit A/D converter pins or use I^2C interface to transfer digital information. A customizable program on the Hoarder board can store the information on a CompactFlash card and/or transmit it to another system in real time using a two-way radio modem.

Since the Hoarder board can collect large amount of information at various periods of time, it is important to time-stamp all the data. The Hoarder board uses a real time clock chip to keep track of time and date. A compact size and low cost makes the Hoarder board a good platform for various wearable applications (Figure 8). One the first activities it was used for was Hackfest 2002 [15] an IAP MIT workshop about wearable computers.

The Hoarder board configuration can be assembled without some of the components. For example, the 2-way radio modem can be left out if the application does not require it. The timer chip may not be necessary if the board is always connected to a computer. The demonstration of the value of hoarder however is in its ability to support user experience experimentation.

Every sign of life. The first application of the Hoarder board was a personal health monitor. The project required a compact wearable device that could collect health information including EKG, temperature, skin conductance, and other parameters over a period of at least 24 hours. The device should also be able to transfer the same information in real time to a computer for visualization. None of existing health-monitoring systems fit these requirements. The Hoarder board with a local storage device becomes a computer extremity that reports what it senses to the computer either in real time or, if it gets to far away, with a delay.

The Every Sign of Life project explores how to make information collected by personal health-monitoring devices fun and engaging, and consequently more useful to the non-specialist. The approach is to design and build computer games and scenarios based on such information. The research focuses on generally healthy people who may be interested in preventing health problems, as opposed to people with a particular disease. The ultimate goal is to make people take care of their own health implicitly by altering their habits and by health-aware planning of their lives. The basic hypothesis is that fun (the fun of learning, achieving, competing) is a way to achieve this goal.

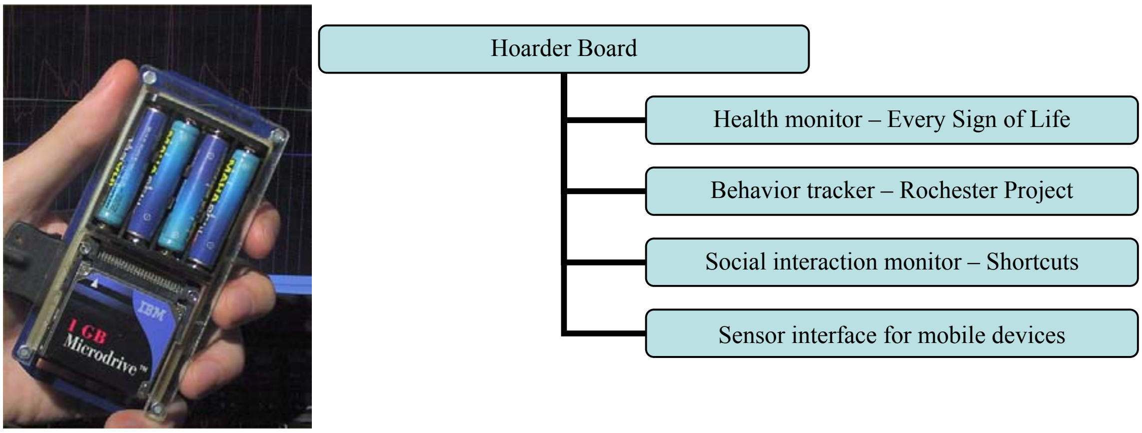

Figure 8 Hoarder board applications

One of the challenges of this project was to design a personal health monitor that can both send vital signs in real time to a computer for immediate interaction and measure them over long periods of time away from a computer. A health monitor we designed consists of the Hoarder board and a biometric board that amplifies EKG, temperature, and skin conductance.

Although the health monitor is similar in what and how it measures to a Holter or event monitor, the Hoarder board-based device is customizable, can gather broader range of information, and can be interfaced to a computer more readily. The health monitor in combination with the software is also designed as a prototype of a consumer device to provide information to the end user as opposed to a healthcare specialist.

The software components, currently under development, include a stress monitor, a heart-beat ball game, and a biofeedback game to explore and possibly improve heart variability characteristics.

The same health monitor can be used in other projects that to analyze various physiological parameters. For example, memory prosthesis [16] designed in the "What was I thinking?" project can potentially use physiological parameters to expand or augment the memory cues.

The extremity computing approach in this project allowed us to define a new mode of user interaction with a health-monitoring device. The two-way wireless link between the device and the PC allows the user to receive real-time health data, load stored information, or change device setting using a PC program. The user does not have to connect the device to the PC or put it into a cradle. The health monitor works as an immediate wireless extension of the PC. Although creating the Hoarder board took an extended period of time, implementing new scenarios with the board requires less effort than with a traditional approach because the board offers hardware and basic software framework to implement sensor interfaces and allows the system creator use well developed programming environments and the rich user-interface capabilities of conventional computers.

Project at Rochester Center for Future Health. The extremity computing devices can also be used to explore behavior of people in various environments. The Hoarder board in combination with a daughter board designed by the Wearable Computing group at the Media Lab is also used in the Smart Home project at the Rochester Center for Future Health [14]. The daughter board has a microphone to keep track of sound, an accelerometer to detect and measure motion, and a tag reader to detect location or proximity to various objects. The system is used as a wearable device to record activities of inhabitants of the Smart Home.

The Hoarder board architecture allowed the Wearable Computing group to easily connect set of sensors of their own and modify the hoarder board software to serve their needs. The group successfully employed the extremity computing approach to implement their own user interaction scenario. Using a conventional computer for user interaction and a wearable component for data gathering allowed them to simplify the system design and made it possible to build and use a larger number of wearable components.

Shortcuts. Another similar example of experimental design with the Hoarder board that employs the extremity-computing approach is the project called Shortcuts by Tanzeem Choudhury [17]. The project explores social interaction between people at the Media Laboratory. A Hoarder board is used in combination with a daughter board and shoulder mount designed by the Vision and Modeling group. The system does analysis of motion, sound, and face-to-face encounters for each individual participant. The Hoarder board digitizes and stores all the data locally on a CompactFlash card. The researchers later analyzed the data to find the information-propagation patterns in a social group. The extremity-computing approach helped to produce data sets from wearable components for analysis on a PC.

Biometrics on cell phones. Even smaller computational devices can have data extremities. The Hoarder board can also be interfaced with other portable devices such as mobile phones. For example the Hoarder board is used in an ongoing project that analyses and displays stress information derived from heart rate variability on mobile phones [18]. The health monitor designed for the Every Sign of Life project uses serial port to transfer EKG to a Motorola phone in real time. The board simultaneously stores EKG on a CompactFlash card for future analysis. The mobile phone provides computational power and a user interface to process and access the data.

In this application the Hoarder board serves as a sensor extremity of a smaller computational device. As in other application the extremity computing approach helps to rapidly prototype both hardware and software for an experimental design.

The Hoarder board can be used not only in wearable, but also in other location-specific applications. For example, the system can be left in an attic or some hard-to-reach place to measure temperature and lighting changes over months or years. The board can stay in power saving mode waking up once in a few minutes or hours to measure the parameters.

Conclusion

The class of extremity computing devices proves to be valuable in rapid design and demonstration of robust scenarios: medical applications for a collaborative exercise game, stress monitoring and feedback, sports training, and many others. We successfully used such devices in creating new wearable and embeddable systems as well as in augmenting existing computer systems with sensor interfaces.

The extremity computing devices provide a computer with practically unlimited sensory capabilities and remove the range limitations of ordinary sensor interfaces. Computers can use data extremities to provide the user with necessary information from multitude of sources around them.

The extremity computing approach expedites systems prototyping by allowing researchers to unify hardware design and engage the rich user-interface capabilities of conventional computers. The approach makes it easy to include sensors into an experimental system. Devices such as HHD or the Hoarder board provide the system designer with a basic framework to connect sensors and implement wireless remote data transfer and gathering capabilities.

The extremity computing also improves user experience by adding sensor capabilities to various objects or to the body and by substituting potentially poor proprietary user interfaces implemented on small devices with a well-evolved rich user interface of a conventional computer. The wireless data-transfer capabilities offered as a part of the extremity-computing concept are a must in many wearable and embeddable scenarios similar to ones discussed in this paper.

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