Editor: Paul Lukowicz ■ University of Passau ■ paul.lukowicz@uni-passau.de

From Backpacks to Smartphones: Past, Present, and Future of Wearable Computers

Oliver Amft and Paul Lukowicz

The 5th International Symposium on Wearable Computing in 2001 (ISWC 01) devoted an entire session to system design. More important, people wearing a broad range of wearable systems filled the conference halls. The exhibition and gadget show, both with a strong focus on wearable hardware, were the centerpiece of the conference. Among the systems shown (and worn) were the IBM Linux Watch, the Carnegie Mellon University (CMU) SPOT platform, the Massachusetts Institute of Technology MIThrill, the ETH WearARM, and the CharmIT system (see Figure 1) that originated at GeorgiaTech (which has been the "workhorse" of wearable enthusiasts for many years).

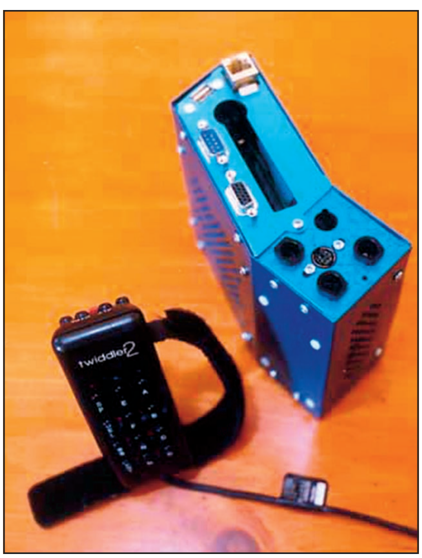

Figure 1. CharmIT. Charmed Technologies began selling this wearable computer as the CharmIT Wearable Computing Kit in 2000.

By contrast, at ISWC 08 not a single paper dealt with computing platforms. More tellingly, only two participants wore computer systems, and no one showed any new platforms at the exhibition. At the same time, by our estimate, around 30 percent (probably more) of the audience had iPhones and comparable smart phones and were using them to access the Internet on a regular basis.

Does that mean that the smart phone has made the wearable computer obsolete? And where does the rise of the smart phone leave wearable computing research?

While voices in the community are talking about the smart phone bringing the "death of the wearable computer" (a panel with this title was actually proposed for ISWC two years ago), we believe that the opposite is true. Today's smart phones in many ways represent the culmination of the ideas that drove wearable systems research in the past. They offer a platform to explore core wearable research topics such as sensing, context awareness, wearable interfaces, and new application concepts. At the same time, the market penetration of smart phones promises to give the results of such research a broad real-world impact.

THE CONCEPT

We can attribute the foundations of wearable computers to the inventions of pocket and wristwatches in the 16th century (en.wikipedia.org/wiki/Watch). Among the first actual wearable computers were the systems to predict roulette wheels of Edward Thorp and Claude Shannon[1] in the early 1960s and that of Hubert Upton to aid lip reading.

In the early 1990s, Thad Starner and Steve Mann at MIT,[2] among others, pioneered modern-day wearable computing. At a time when computing had just entered the home with large, clumsy PCs, they envisioned computers that:

- they could always have with them and use any time and any place, not just at the desk;
- have interfaces that would make them usable even while a person is physically and mentally engaged in a complex real world;
- augment human perception and mul-

Published by the IEEE CS ■ 1536-1268/09/$25.00 © 2009 IEEE

Figure 2. Private Eye. Thad Starner sports wearable computing gear in 1993.

Figure 3. Xybernaut. This wearable system was among the first commercial solutions of the 1990s.

tiply human mental capabilities; and
- have awareness of the physical environment and can incorporate this awareness in their functionality.

Clearly, no off-the-shelf computing devices existed at the time that fitted such a vision. Thus, the search for appropriate wearable computing devices became a key research question.

THE PAST

For the subsequent development of wearables, we highlight trends in computing platforms while omitting many further foundational details. Bradley Rhodes and many contributors compiled a summary of historical events from which we took some of the information in this review (www.media.mit.edu/projects/wearables/timeline.html).

In the 1980s, rapid electronic miniaturization and convenient availability of computer parts led to several wearable computers that addressed specific applications, such as Steve Mann's 1981 backpack-mounted computer to control cameras. In the '90s, increasing processing performance paved the way for general-purpose wearable computers that allowed mobile users to perform classic desktop computing tasks. Many of the early systems were worn at the waist, as locations close to the center of body mass made it easier to deal with device sizes and weight. Among these systems were Doug Platt's Hip-PC in 1991, based on a Intel 80286 processor. This system served as basis for MIT's Lizzy, which Starner wore in 1993 along with a Private Eye head-mounted display (HMD) and a one-handed keyboard, called Twiddler (see Figure 2).[3] In 1990, one of the first commercial solutions—the Xybernaut—appeared on the market (see Figure 3). The standard Xybernaut system setup consisted of a belt-attached computing block and a carry-on display.

In 1994, Edgar Matias and colleagues presented a wearable computer based on a small display and a half-QWERTY keyboard for one-handed operation (see Figure 4). Both devices were attached to forearms.[4] By moving the arms close together, the wearer could type and watch the input simultaneously. Matias commercialized this solution. IBM researchers followed the half-keyboard concept with a "belt computer" (www.almaden.ibm.com/cs/user/inddes/halfkb.html). Panasonic presented a similar product, called the Brick Computer, in 2002. The Brick was coupled wirelessly to an arm-worn display. Many companies introduced concept studies of arm-worn computers in the '90s and beyond. A few systems achieved market success, such as Vocollect (www.vocollect.com), a wearable voice-directed logistics solution, as well as the Symbol Technologies wireless barcode scanners.

Since the early 2000s, various mobile computers have appeared on the market, such as the Sharp Zaurus (en.wikipedia.org/wiki/Sharp_Zaurus) and the Nokia N770 (www.nokia.com) that eventually led to the diversified product range of thin clients and smart phones today. In parallel, research systems appeared, such as the Linux Advanced Radio Terminal (LART) embedded computer by TU Delft and the SPOT, which succeeded the previous VuMan wearable generations from CMU. The TU Delft

WEARABLE COMPUTING

Figure 4. Half keyboard. Edgar Matias and his colleagues developed this system in 1994. Systems using the half-keyboard approach are available from the Matias Corporation (www.matias.ca).

Figure 5. WearARM. A flat profile wearable computer that used flex-print technology to interconnect components, introduced by ETH Zurich in 2001.

Figure 6. IBM Linux Watch. Integration of a complete computing system into a wrist-worn device, presented in 2000. (image courtesy of IBM Research).

developers made the LART design available as open source to researchers interested in using the embedded system in their own applications (www.lartmaker.nl).

Besides waist-attached and backpack-worn units, researchers investigated further integration concepts in the early 2000s, such as the Compaq Itsy, a pocket computer for speech recognition and real-time movie decoding.[5] Researchers at ETH Zurich investigated approaches to clothing-attached electronics resulting in the WearARM computing core in 2001 (see Figure 5).[6] The WearARM used flex-print technology to interconnect components in a flat system profile.

In the '80s, technological challenges related to size, power consumption, and weight constrained the development of wristwatch computers to simple calculators. But in 2000, Chandra Narayanaswami and his team at IBM presented a highlight of wristwatch integration work with the "IBM Linux Watch" (see Figure 6). In 2004, the ETH Wearable Group introduced the Q-Belt Integrated Computer (QBIC) as a new research platform (see Figure 7)[7] in which developers integrated the actual computer into a belt buckle. They attached peripherals and interfaces, such as batteries, HMDs, and sensors to belt-integrated connectors. Researchers continue to use this system in real-world data recording and activity recognition investigations today.

Many researchers' developments and application reports made clear that comfortable interaction with mobile and wearable computers is a major challenge, related to managing the user's attention and providing convenient controls for information entry. Various see-through and look-around HMDs have been developed that instantly switch focus between computer and environment. The most convenient HMD might eventually overlay a wearer's actual vision with additional information and cues. Researchers have conducted various investigations to augment reality in this way, such as Eyetap goggles (www.eyetap.org). Bruce Thomas and his colleagues developed the Tinmith system (see Figure 8) to study information overlay outdoors, using a wearable computer (www.tinmith.net). (For more information on Thomas and his colleagues' work, see "Through-Walls Collaboration" on page 43.)

Sensors served as additional and later even primary information sources for wearable computers, with the goal of supplementing or even replacing manual information entry by context

Figure 7. Q-Belt Integrated Computer (QBIC). ETH Zurich introduced QBIC for use in research and as a design study in 2004.

awareness. Consequently, mobile and wearable computing systems became a prerequisite to record sensor data in research studies on context recognition. One historical example of a distributed sensing and processing system is the MIThril jacket of MIT, first presented around 2003 (www.media.mit.edu/wearables/mithril).

Some approaches went even further in this direction, aiming at integrating complex electronics directly into clothing, such as jacket developments by Philips, Levis, and Infineon. Researchers often envisioned an entire general-purpose computer implemented on a textile substrate as the ultimate "smart garment."

THE PRESENT

In 2007, Eurotech introduced the Zypad WL1100, a wrist-worn touchscreen computer, to the market for emergency, security, logistics, and further applications (see Figure 9; www.arcom.com/wearable_computer/Zypad/default.htm). The device includes a number of sensors, such as GPS, motion, and audio to extend information input and functionalities. Another device widely used in the wearable computing community has been the OQO touchscreen PC (see Figure 10; www.oqo.com). It's small enough that users can comfortably wear it on the belt, features PC-like functionality, and has a broad range of interfaces such as USB host, Bluetooth, WLAN, and VGA. While such devices are still too bulky for everyday consumer use, they're perfectly satisfactory in many industrial applications. The main remaining concern is battery runtime, which remains well short of the typically required 12 to 24 hours. Another concern is the connections to peripherals such as HMDs or specialized sensors, which often require bulky on-body cabling.

Figure 8. Tinmith. Wearable system that overlays computer information on the wearer's view, introduced by the University of South Australia in 2003.

In parallel to the aforementioned developments, recent years have shown an explosion in smart phones' performance and functionality. Systems such as the iPhone and the Android phone are powerful computers running full-scale operating systems equipped with a broad range of sensors. Being mainstream consumer devices, they have a form factor that's widely accepted for everyday use. As a consequence, the wearable research community has been increasingly adopting them, in particular for long-term sensor data collection and activity recognition applications.

The default interaction with a mobile phone currently doesn't follow the wearable concepts. Typically, it requires the use of both hands and full user attention. Thus, it isn't possible to use the device while engaged with real-world tasks, which is a key attribute of wearable systems. However, with interfaces such as Bluetooth headsets, consumer-oriented HMDs (such as the MyVu, for the iPhone; www.myvu.com), and simple keypads embedded in jackets (such as the Burton jacket for skiers; www.burton.com), smart phones are increasingly becoming true wearables.

Figure 9. Zypad WL1100. Eurotech introduced Zypad in 2007 as a wrist-worn wearable computer for emergency, security, logistics, and further applications. (image courtesy of Eurotech)

Figure 10. OQO: A hand-held touchscreen computer that has been widely used in wearable computing research.

The key issues with current mobile phones is that they don't offer sufficient flexibility for combining different functional modules and provide limited connectivity for additional sensors or interaction devices. Often phones just provide Bluetooth, which seems inappropriate for interconnecting small distributed sensors with the required runtime of several days. This has motivated ongoing development of platforms with a focus on modular

WEARABLE COMPUTING

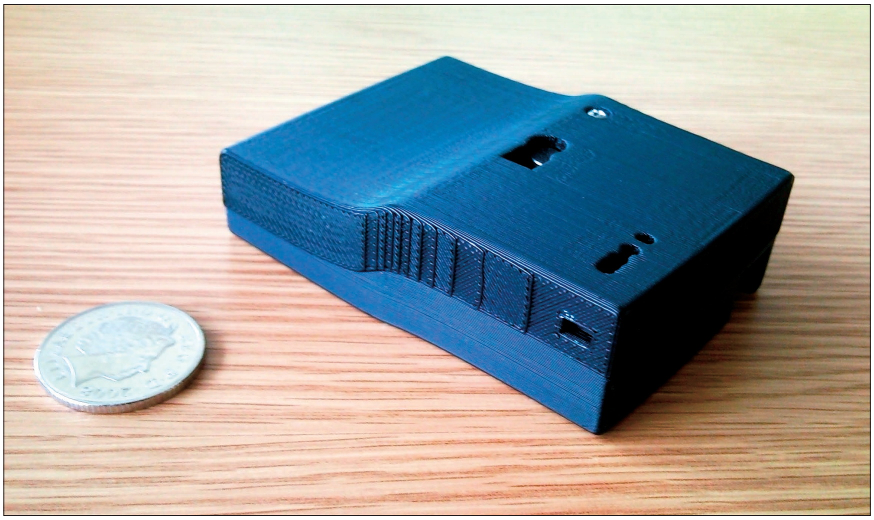

Figure 11. Mobile sensing platform (MSP). A mobile sensing platform supporting different sensor combinations, introduced in 2008.

sensor configurations. As an example, in 2008, Tanzeem Choudhury and her colleagues from Intel, the University of Washington, and Stanford presented a mobile sensing platform (MSP) for activity recognition research. The MSP used a module concept to attach different sensor modules. Similar efforts are underway in related communities, such as pervasive health and body sensor networks.

THE FUTURE

Our discussion shows that although existing smart phone platforms certainly aren't perfect from the point of view of wearable applications, the main concerns aren't the computing units and their form factors. The key issue is the connectivity between the main computing unit (which will remain some sort of commercial, mobile phone-like "brick") and other devices, sensors in particular. The latter are what really differentiate a wearable system from a mobile phone. In most cases, the other devices should and will be tightly integrated and possibly even built with textile technology. Thus, it seems that there's little space for further research on dedicated wearable computing platforms. We also argue against the classical wearable vision of a computer (or for that matter, a phone or a MP3 player) that's fully integrated into clothing (possibly even built on a textile substrate). Instead we envision future wearable systems that consist of four main layers:

- Mobile phone-like device as central on-body platform for general purpose computing tasks. It will likely remain a standalone device carried in a pocket or a holster, not integrated in clothing. However, we're likely to see vastly improved connectivity to other devices and sensors, possibly including interfaces to textile electronics.
- Carry-on peripherals such as headsets, displays, and textile touchpads. Such peripherals will facilitate real wearable interactions, making the system usable even when the user is interacting with the real world.
- Microsensors deeply embedded in accessories, such as rings, shoes, and belts, and, in some cases, encapsulated in clothing. Such sensors are essential to provide the system with environmental awareness and implement many health and sports related applications.
- Sensing, communication, and power generation infrastructure that isn't just built on textiles, but actually implemented in textile technology. Such infrastructure is optimally suited to leverage the advantages of clothing and textiles, such as that they're attached to certain body parts (important for sensing) or span entire body parts (relevant for communication and large area power generation—for example, using solar cells).

These layers should seamlessly interoperate, allowing applications running on the main computing device to make automatic transitions between interfaces and sensing setups as the user changes clothing.

Initial signs are already emerging that systems are moving toward the type of architecture we describe. The Bluetooth headset is a good example of a widely accepted carry-on peripheral that allows the user to interact with mobile phones while walking or driving. Nike recently introduced running shoes with an acceleration sensor wirelessly communicating with an iPod or iPhone, which nicely illustrates the concept of an embedded microsensor. Increasingly, textiles provide the infrastructure for technology, such as sports jackets providing "cable channels" for headphones as well as simple textile touchpad sleeves that, for example, let skiers operate their mobile phones without removing their gloves. Researchers have also demonstrated clothing-integrated solar cells.

While the emergence of smart phones as widespread versatile mobile platforms has rendered classic, general-purpose wearable computing devices obsolete, their emergence is a powerful enabler for a wide range of wearable concepts, systems, and applications.

ACKNOWLEDGMENTS

The authors are grateful to many researchers who have contributed photographs of their wearable computers for this article. Moreover, the authors thank Thad Starner for his comments on an earlier draft of this article. EU WearIT@Work project partly sponsored the author's work.

REFERENCES

1. E.O. Thorp, "The Invention of the First Wearable Computer," *Proc. 2nd Int'l Symp. Wearable Computers* (ISWC 98), IEEE CS Press, 1998, pp. 4–8.
2. T. Starner, "The Cyborgs are Coming, or, the Real Personal Computers," tech. report TR-318, Media Lab, Mass. Inst. Tech., 1993.
3. T. Starner, "Lizzy: MIT's Wearable Computer Design," 1993; www.media.mit.edu/wearables/lizzy/lizzy/index.html.
4. E. Matias, I.S. MacKenzie, and W. Buxton, "Half-QWERTY: Typing with One Hand Using Your Two-Handed Skills," *Companion Proc. Conf. Human Factors in Computing Systems* (CHI 94), ACM Press, 1994, pp. 51–52.
5. W. Hamburgen et al., "Itsy: Stretching the Bounds of Mobile Computing," *Computer*, vol. 34, no. 4, 2001, pp. 28–36.
6. P. Lukowicz et al., "The WearARM Modular, Low-Power Computing Core," *IEEE Micro*, vol. 21, no. 3, 2001, pp. 16–28.
7. O. Amft et al., "Design of the QBIC Wearable Computing Platform," *Proc. 15th IEEE Int'l Conf. Application-Specific Systems, Architectures and Processors* (ASAP 04), IEEE CS Pres, 2004, pp. 398–410.

Oliver Amft is an assistant professor at TU Eindhoven. Contact him at amft@tue.nl.

Paul Lukowicz is a full professor at the University of Passau. Contact him at paul.lukowicz@uni-passau.de.