Wearable Computing

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What Will We Wear After Smartphones?

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In 2009, this department featured an article titled, "From Backpacks to Smartphones," signifying the trend toward smartphone use in many aspects of wearable computing research.[1] For the first time, smartphones were implementing several key properties of wearable computers—not only providing a convenient platform for prototyping on-body systems but indeed blurring the boundary between mobile and wearable computing. Suddenly, it was feasible to implement large-scale behavior analysis studies—for example, understanding dwelling locations, determining user context and frequent conversation partners from acoustics and movement, or conveniently assessing physical activity.[2]

However, when looking at the sessions of wearable computing conferences over the past few years—including the International Symposium on Wearable Computers and the International Conference on Wearable and Implantable Body Sensor Networks—the prominence of smartphones has declined. Although smartphones remain a wearable research tool, often as a body-hub or prototype for data analysis—we're now starting to see more integrated systems in daily accessories, smart textiles, and flexible on-body patches. Moreover, wearable computing is no longer constrained to one or two conferences of enthusiasts, as was the case in the early days. In fact, other research communities, including computer-human interaction, are frequently hosting wearable computing sessions (for example, CHI 2014 hosted a wearable computing exhibit curated by Clint Zeagler and Thad Starner). Exceeding promises of the early days, wearable computing has indeed entered the business world, with presentation tracks and product booths at industry events, including the Consumer Electronics Show, the IDTechEx Show, and the CeBIT Expo.

Does this progress mean that wearable computing research will now pursue minor incremental improvements of methods and solutions? Are we done with major breakthroughs? If so, should investigators move to new strands, such as the Internet of Things (IoT) and machine-based sensor data interpretation? And what should we make of reports regarding the lack of sustained business success of wearables such as smartwatches and activity trackers, with users quitting after 6–18 months of use?[3]

Sustainability might indeed be the grand challenge. In fact, the EU recently funded the Wear Sustain initiative (http://wearsustain.eu), which pushes creative industries to engage with technology industries though calls for bottom-up projects. Yet it is precisely because of this challenge that we believe wearable computing is entering its most exciting phase yet, as it transitions from demonstrations to the creation of sustained markets and industries, which in turn should drive future research and innovation.

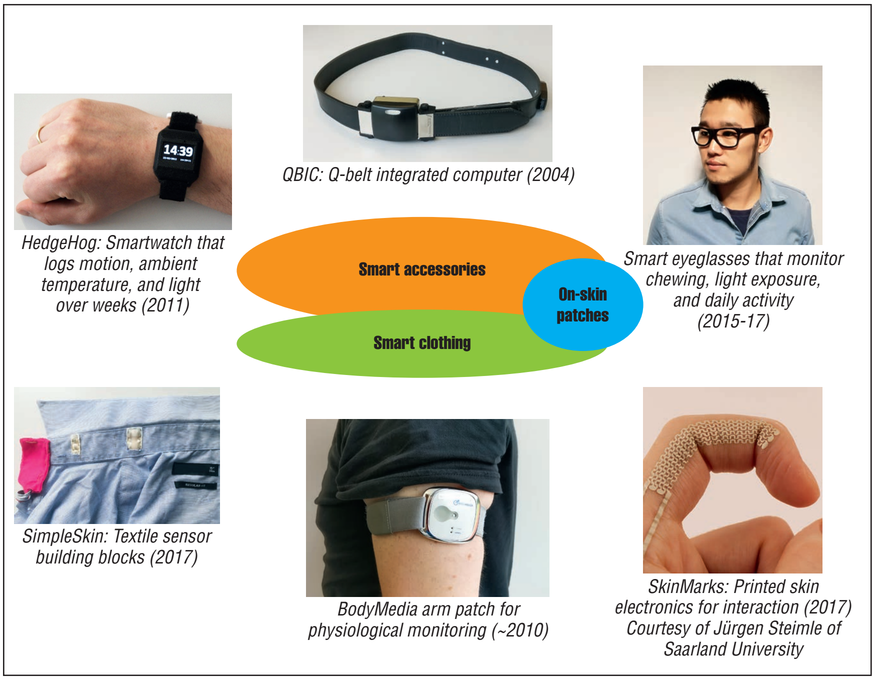
REVIEWING MARKET DEVELOPMENT

Over the past two decades, we have witnessed the market's evolution from bulky carry-on electronics to smartphones and now computing-integrated everyday accessories, clothes, and body patches.

The approach of the early days was to realize computing on the body by replicating the input, output, and processing of personal computers. Early examples included the Twiddler (currently in its third version, twiddler.tekgear.com) and the Matias half-keyboard, worn on one forearm and used with a display on the opposite arm (www.matias.ca). The various commercial head-mounted displays (HMDs) of the 1990s and early 2000s provided the interface for carry-on computing units, including the 1990 Xybernaut, the 2002 Panasonic "Brick," and the 2007 Zypad and OQO, all of which were aimed at commercial success.

Later approaches migrated to sensor-mediated (or exclusive sensor-based) data and information input. During the late 2000s, and driven by the success of smartphones, the wearable computing paradigm led integrated circuit manufacturers to propose various miniaturized, low-power platforms for wearable systems development that either integrated sensors as systems-on-chip or

Published by the IEEE CS ■ 1536-1268/17/$33.00 © 2017 IEEE



HedgeHog: Smartwatch that logs motion, ambient temperature, and light over weeks (2011)

QBIC: Q-belt integrated computer (2004)

Smart eyeglasses that monitor chewing, light exposure, and daily activity (2015-17)

SimpleSkin: Textile sensor building blocks (2017)

BodyMedia arm patch for physiological monitoring (~2010)

SkinMarks: Printed skin electronics for interaction (2017) Courtesy of Jürgen Steimle of Saarland University

Figure 1. Categories of wearables today and examples illustrating the diversity of systems and applications.

provided interfaces for sensors, displays, and actuators.

Today, many in the wearables industry are trying to build on high-volume, low-cost smartphone components to create secondary markets. A primary example is smartwatches (and other wearables) with integrated inertial measurement units. The InvenSense MPU-92xx family (www.invensense.com), for example, is a frequently used inertial measurement unit. But the InvenSense device does not only provide digital acceleration, gyroscope, and earth-magnetic-field sensor readings in one 3 × 3mm multichip package, it also supports microcontrollers with built-in feature computation, sensor-orientation estimation, and basic pattern-recognition functions.[4]

CATEGORIZING TODAY'S WEARABLES

Today's wearable computing systems can be categorized as follows (see Figure 1):

- smart accessories, including earwear, wristwear, eyewear, shoewear, and beltwear;
- smart clothing; and
- smart on-skin patches, including electronic plasters and tattoos.

The unprecedented market success of activity trackers has fueled the wearables market far beyond the quantified self. For example, Bragi (www.bragi.com) markets wireless earbuds for music playing and communication in addition to sports activity recognition. Smartwatches from Apple and others aim to extend the smartphone to the wrist with sensing, information display, and interaction capabilities. However, aside from smartwatches and wristbands, most commercial "wearable" systems today still appear as a clip-on to clothes or limb straps, rather than being actually integrated in everyday accessories.

As for smart clothing, there is still only a handfull of systems that scale beyond the prototype level. Myant (www.myant.ca) is developing garments with integrated electrodes and sensors for heartbeat and muscle activity monitoring. On the interaction side, Google's Project Jaquart (https://atap.google.com/jacquard) is developing yarns for touch and gesture interfaces.

Similarly, the market for on-skin patches is currently small, and various technical challenges exist regarding cost, durability, bio-compatibility, and low-power operation. Nevertheless, the growth potential of skin patches is promising. Companies such as MC10 (www.mc10inc.com) are prototyping skin patches for physiological monitoring, including important physiological variables: hydration, temperature, and others.

UNDERSTANDING THE CHALLENGES

The application space of wearable systems is highly diversified, as the previous examples indicate. Not only does each sector, from logistics to medical assistance, have its own separate requirements for system implementation and features, but there are many distinct niche applications within the sectors, seeking specific functionality and design.

Application Diversification

The app concept for smartphones is an excellent example of how to deal with diversified user needs: development is focused on small software applications on a common hardware platform. In contrast, wearables are created by combining specific functionality in hardware, software, and design, thus limiting developers in addressing several potential wearable markets with one solution (see Figure 2).

Just in the accessories field, software apps for smartwatches or smart eyeglasses[5] can provide wearers with alternative functions, but are constrained by the form factor, body position, or the device's use model—sports watch or business watch, for example. Google Glass illustrates the *diversification challenge* for an individual wearable device.

Although the preliminary investigation of Glass by many researchers resulted in a variety of applications, its current use is narrow, dominated

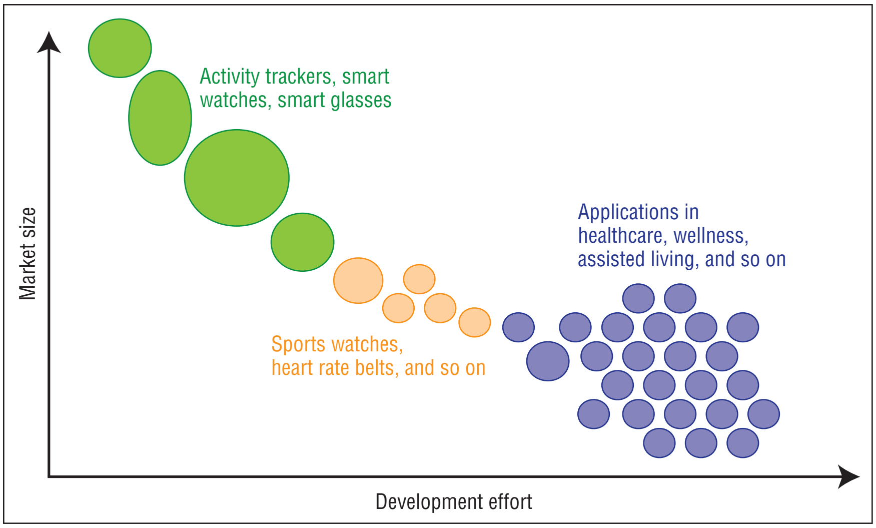


Figure 2. The "market size versus development effort" dilemma in wearable computing. In this qualitative illustration, dots represent examples of wearable computing applications, and their size represents the application bandwidth.

by logistical applications and process-optimization needs in manufacturing.[6] Diversification thus requires considerable effort in terms of individualized development for each application-specific wearable system.

With recent advances in integrating technology into wearables—such as in daily accessories and textiles—using high-volume electronic components is no longer a limiting factor in terms of development effort and product cost. In particular, wearables in healthcare, wellness, and assisted living have relatively small individual market volumes, even though they represent a promising application sector. However, the "market size versus development effort" dilemma cannot be resolved merely using established wearable computing methods. Developers also need robust novel production processes and reliable platforms.

Dealing with Uncertainties

Compared to other IT segments, wearable computing has a low barrier for communicating potential technology benefits to wearers. Because of this low entry barrier, many startup teams are pursuing wearables—from rings to smart glasses and service ideas—successfully using crowdfunding to finance the development and business initiation. Yet many have ultimately ended up as *vaporware*—that is, "good ideas incompletely implemented" (http://downloads.oreilly.com/radar/r1/11-83.pdf). Even those startups and businesses that do eventually succeed often undergo highly critical phases in their development, marked by delays (of months if not years), changes in product concepts, a reduction in features, and user complaints of broken products.

Although development experience in wearable hardware and software is a key to success, teams underestimate the hurdles to realizing reliable products. Here, in particular, embedding electronics into accessories, patches, and so on requires research in reliable processes and the standardization of evaluation methodologies.

IDENTIFYING NEW DRIVERS

Until the early 2000s, research around wearable computing centered on device development, input and output modalities, and context awareness, with the latter representing much of what was covered in ISWC proceedings. Although classic PC-like input and output has practically disappeared, context awareness continues to dominate the research programs, supported by novel sensing approaches, progress in sensor integration, and advances in machine learning. Interaction research is also exploring the use of wearables, further pushing context awareness and demonstrating how wearable computing has matured as a research field such that it's now ready to share its methods and tools. We observe a similar convergence in sensor-based context awareness, which shares methods with fields such as computer vision.

Advances in smart materials over the last few years have just begun to stimulate the wearable computing field in entirely new ways. For example, the skin patches and electronic tattoos that have recently been introduced for physiological monitoring are made of new stretchable, conductive, and skin-compatible materials (see "milestone 5" in the "Beyond Smartphones" sidebar). New smart materials with different elasticity, conductivity, and changeable mechanical properties can provide the basis for new production approaches that could replace the rigid printed circuit boards in wearables, where body contact, form factor, and skin-like properties are key.

Substantial advances in production and process technology are also coming up, which could simplify the development and prototyping of wearable devices. For example, ink-jet printing enables designers to print small-pitch conductive traces for interconnects in flexible electronics. Furthermore, bio-printing, offered by nScrypt (www.nscrypt.com), for example, lets researchers print tissue—possibly with sensing capabilities in the future. Figure 3 shows wearable computing's potential influence on future solutions using a variety of input methods.

OUTLINING FUTURE RESEARCH

So what lies ahead for wearables researchers? We foresee a variety of exciting research challenges and future trends for wearable computing.

BEYOND SMARTPHONES

Wearable computing research recently passed the 20-year mark, having grown from a gathering of like-minded, mostly US-based, researchers into a strong, diverse, and international scientific field.

KEY MILESTONES

Here we provide a summary of key milestones in the development of wearable computing.

1: A Wearable Prediction System

Although the foundations of wearable assistive devices can be seen in early pocket watches of the 16th century, most consider the wearable system by Edward Thorp and Claude Shannon in the 1960s that predicts the outcome of a roulette wheel as a starting point for wearable computers.

2: Digital Hearing Aids

In the 1980s, digital hearing aids entered the market. Although they were imperfect at the time, they addressed a major patient concern and fulfilled even today's definition of wearable computing systems.

3: New Concepts in the 1990s

The modern concept of wearable computing was developed in the early 1990s by Thad Starner and Steve Mann, among others. At a time when PCs were entering offices and homes, Starner and Mann envisioned systems that would always be with the user, integrated into everyday outfits, aware of the physical environment, and thus able to augment human perception.

4: Smartphones

Although various business ideas—including those focused on smart shirts and wrist-worn computers—found niche markets in the late 1990s and early 2000s, it was the advent of smartphones in 2005 that really opened up opportunities for wearable systems. With the emerging mass market, high-volume production of low-power integrated circuits, digital sensors, and systems-on-chip made a variety of wearables viable, including activity trackers and sports watches.

5: Technology Integration

More than a decade after the technological opening through smartphones, we consider the novel technology integration approaches to be the next milestone. Examples include on-body electronic patches,[1] computer-augmented accessories that (more than ever) resemble their traditional counterparts, and novel approaches in smart textiles.[2]

ONGOING RESEARCH

The scientific literature on wearable computing shows a host of application opportunities in addition to many open research challenges. Bruce Thomas's discussion of the "ultimate wearable computer" highlighted the progress from bulky devices to smartphones and diverse application explorations, leading to a multidisciplinary research community of electronics, computer science, art and design, and fashion and materials.[3] Also, one of us (Oliver Amft), along with Attila Reiss, reviewed "real" wearable computers to investigate the persisting challenges for integrating computing, sensors, and interaction in form factors of daily accessories and clothing.[4] The review highlighted the fact that technology integration in real everyday life is essential in many areas to achieving wearer compliance. Currently, there is still a lack of integrated solutions and prototypes, which would make the development path sufficiently repeatable.

Lukasz Piwek and his colleagues reviewed health wearables and described concerns regarding safety, reliability, and security, concluding that primarily users who are already health-aware could benefit.[5] Mary Ellen Berglund and her colleagues observed a recent preference for wrist-worn wearables, warning that the trend could limit creativity in exploring other areas of wearables.[6] And Dan Siewiorek, in a recent retrospective, emphasized ongoing challenges in attention management, wearer comfort, and the powering of wearables.[7]

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Resilience and Long-Term Validity

As wearable technology continues to advance on almost every front, it's hard to imagine a single product lasting more than a few months before a better version (in terms of processing, display, or battery life) comes along. The current market is built on the fact that hardware components are cheap and small, making it easy to buy replacements and grow our drawer-collection of "obsolete gadgets."

This is not solely a hardware issue, either. Wearable sensors—and the data they produce—change with every replacement as well, making it hard to design a wearable service that remains in operation beyond several months. We need to develop methods for collecting consistent data with wearables over longer time spans.

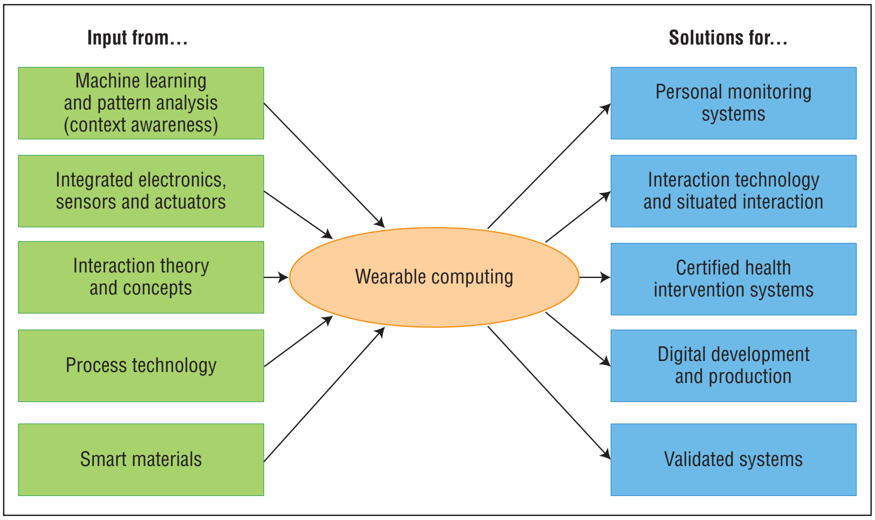

Figure 3. How wearable computing might be influenced by and influence future research.

Benchmarks and Evaluation

Many wearable products are sold as a life-enhancing or health-improving accessory that, when worn, promise a variety of benefits. Good examples include fitness trackers that display caloric expenditure and sleep trackers that display the wearer's different sleep phases during the night, but how accurate are these estimates? It's clear that many devices can easily be fooled and that most wearables on the market today have not undergone thorough (clinical) testing—such as those for sleep estimation.[7]

For each wearable application, from step counters to HMDs, we'll need to find out what systems and algorithms perform best and which evaluation method is the most rigorous for the job. However, we can't foresee all situations, so we must also identify system limits. Wearables need to declare side effects, co-conditions, and limitations, similar to what's done for medications.

Sustainable Software

Many current wearables have been designed from scratch, including home-grown software. The few operating systems for wearables form a very messy landscape that lacks developer guidance. There are many design options complicating the software for wearables, from custom microcontroller code to Arduino sketches and Android Wear Apps, depending on available system resources and applications. Although wireless Internet access even in the smallest devices lets developers run online updates and delegate computation to a cloud, it's likely insufficient to scale wearable software development.

Wearable system software needs (standard) frameworks that fit an increasing pool of diverse devices. Moreover, we need software frameworks for critical applications in certified health intervention systems—wearables for providing time- or measurement-dependent medication, for example.

Wearer Compliance

Whether it's new smart eyeglasses or a body patch, technology integration has been a highly underestimated feature of wearable system development and user compliance, particularly for personal monitoring and intervention applications. So far, few products go beyond the concept of the carry-on gadget to truly integrate computing into practical accessories, garments, and so on.

We need research into integration methods and tools, as well as demonstrations. In the near future, a multitude of widely diverse mobile and wearable systems will reside in the personal space of every user, making generic interoperability the critical factor for wearer compliance. Such interoperability must scale beyond individual applications that share, for example, a text message on different devices.

Market Size vs. Development Effort

Addressing low-volume markets is a key element to making wearables successful in the next decade. There are already research efforts underway to develop wearable technology that lets businesses scale across small applications. For example, the EU-funded SimpleSkin project (simpleskin.org) developed fabric material that lets developers realize different sensor functions, while textile manufacturers could mass-produce the generic fabric in standard processes.[8] "Sensor-ready" garments thus could be produced, with electronics or even software determining the functionality.

Moreover, novel smart materials and printing methods are helping designers and researchers not only prototype ideas but also develop digital production processes. Digital production can be used to help realize the design[9] or function[10] of personal products.

Between the hope and hype, wearable computing has always aimed for more personal, intimate computing, and in looking ahead, we foresee many interesting research opportunities. Wearables have transitioned from single, general-purpose computers to a set of devices, each with its own challenges. Consequently, core wearable research must grow beyond the well-established topics in context-awareness, sensor, and interaction research, providing new methods and tools for truly integrating computing with the body and creating real-world impact.

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