22 Design Challenges of Real Wearable Computers

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22.1 INTRODUCTION

The foundations of wearable computing may lie in pocket and wrist-worn watches that were invented in the sixteenth century. Thorpe and Shannon are credited for being among the first researchers attempting to build wearable computers in 1961. Their motivation was to beat statistics and increase chances of winning in card games and roulette (Thorp, 1998). While their wearable systems were rudimentary by today's technology standards, they battled with integrating critical features that are key components of a wearable computer until today: sensing or information input, computing, and some form of actuation, feedback, or communication of retrieved information. Thorp and Shannon's solution was based on game status input using a shoe-integrated button, computing using a carry-on device hidden in cloths, and information feedback using an audio ear pad, all to avoid being detected by the game clerk. Between the 1990s and today, wearable computers gained commercial and research interest and first *on-body* computing products appeared in the markets. In the 1990s, on-body computer solutions were often derived from standard computing components available at the time, such as the half-keyboard (Matias et al., 1994) and backpack or side-case worn embedded computing units (Lizzy, 1993; Starner, 1993). As more integrated sensors became available, the view on market opportunities shifted from using on-body computers for mobile data entry applications, such as in warehouse management, to fitness, sports, and the quantified self. However, a substantial share of today's commercial on-body systems, such as the Nike running gear (shoe sensor plus mobile carry-on device), still follows a similar technical approach as in the early solution of Thorpe and Shannon: the on-body computer solution is centered around a mobile carry-on device that provides computing, and often also sensing and actuation/communication functions. Similarly, many research efforts during the past years considered smartphones and other carry-on devices as basis for wearable computers. Devices are often placed in pockets, attached to glasses, or strapped to body parts, without actually considering the integration into a wearable system.

The vision of invisible computing set out by Mark Weiser (1991) suggests that technology shall not require particular consideration during everyday life, be virtually invisible, and thus not hinder physical activity. Consequently, electronic devices that add features to wearable systems, including computing, sensors, etc., must be unobtrusively embedded in a user's outfit. In its ultimate form, *real wearable computers* thus become part of a regular garment or accessory that is already used. Toward the integration of wearable computers, various challenges exist that affect function, robustness, and various other design considerations. For example, when integrating computing into a finger ring, space constraints critically affect the design, besides aesthetic requirements of the ring as an accessory. Rather than space, wearable computers integrated in garments are mostly constraint to textile material properties such as breathability and stretchability.

In this chapter, we review projects that investigate the integration of wearable computers in garments and accessories. Our goal is to provide readers with an overview and in-depth understanding of the technical challenges and best practices of wearable computer integration, thus wearables that could become useful in everyday life situations. In particular, we summarize technical design challenges and lessons learned, and provide directions for future research on real wearable computers. The analysis emphasizes work toward the integration of sensing, computing, and actuation with (1) textile fabric to obtain garment-based wearable computers and (2) commonly used body attachments to obtain accessory-based wearable computers as detailed in the following section.

22.1.1 Review Inclusion and Exclusion Criteria

Various technical challenges exist for integrating wearable computers in garments and accessories, which is the focus of this review of research literature. An essential prerequisite for real wearable computers is that the base purpose of a garment or accessory must be retained when integrating electronics:

Garment-based wearable computers. Garments need to provide cover and protection from environmental effects, such as water, temperature, and fire, when adding wearable computing. Similarly, garments may serve as fashion showcase. Examples include shirts, gloves, pants, and shoes.

Accessory-based wearable computers. Accessories shall retain their purpose for assistance or aesthetics when adding wearable computing. Examples include goggles, rings, and belts.

Similar to smartphones, various other carry-on devices exist, such as belt clip-on embedded computers, activity trackers, and the Google Glass. Following our focus to identify integration solutions and open challenges, carry-on devices were not considered. Furthermore, work that emphasizes only one aspect, such as sensor integration in textiles or sensor data processing, without considering the complete wearable computer solution was excluded from the analysis. While we mention commercial products throughout this work, our analyses focused on research investigations along the objectives mentioned earlier.

Based on web searches, we included 20 individual projects on garment-based wearable computers and 13 projects on accessory-based wearable computers that were published between the first *Fundamentals of Wearable Computers and Augmented Reality* book edition in 2001 and June 2014. Projects were then categorized according to wearing position and subsequently analyzed.

22.2 GARMENT-BASED WEARABLE COMPUTERS

Garment-based wearable computers have been designed and implemented for a variety of applications, including remote health monitoring, physical activity monitoring, and general user interaction. The following summary highlights important applications and selected projects. Subsequently, we discuss the placement-specific analysis in this section. Table 22.1 summarize the individual garment-based projects included in the analysis.

TABLE 22.1
Garment-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: head and neck *Form*: headband	U-healthcare: smart headband for remote health monitoring (Kim et al., 2008)	*Computing*: microcontroller *Sensors*: PPG, accelerometer, GPS *UI*: none *Communication*: ZigBee
Location: head and neck *Form*: neckband	Capacitive neckband for activity recognition and nutrition monitoring (Cheng et al., 2010)	*Computing*: MSP430 microcontroller *Sensors*: capacitive electrodes *UI*: none *Communication*: ZigBee
Location: torso *Form*: shirt	SMASH: distributed computer for body posture monitoring (Harms et al., 2008)	*Computing*: MSP430 microcontroller *Sensors*: accelerometers *UI*: buttons, LEDs *Communication*: I^2C, SPI, Bluetooth
Location: torso *Form*: shirt	CHRONIUS: instrumented shirt for physiological monitoring (Rosso et al., 2010)	*Computing*: microcontroller *Sensors*: ECG, respiration rate monitor, pulse oximeter, temperature sensor, accelerometer, microphone *UI*: none *Communication*: Bluetooth
Location: torso *Form*: vest	MIThril: computing architecture for wearable context-aware research (DeVaul et al., 2001)	*Computing*: MPC823 microprocessor, SA 1110 StrongARM microprocessor *Sensors*: microphone, accelerometers *UI*: Twiddler, Palm keyboard, HMD *Communication*: I^2C, USB, Dallas Semiconductor one-wire protocol, 10Mbs Ethernet, 802.11 WLAN
Location: torso *Form*: vest	WearARM: computing core for wearable applications (Lukowicz et al., 2001)	*Computing*: SA 1110 StrongARM microprocessor, TMS320 DSP *Sensors*: grayscale cameras, proximity sensor *UI*: keyboard, mouse, HMD *Communication*: I^2C, USB, serial port, IrDA port, PS/2, VGA, 10Mbs Ethernet, 802.11 WLAN

(*Continued*)

TABLE 22.1 (*Continued*)
Garment-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: torso *Form*: vest	SensVest: vest-integrated activity monitoring system (Knight et al., 2005)	*Computing*: no information *Sensors*: HR monitor, temperature sensor, accelerometer *UI*: LED, LCD display *Communication*: RF transmission (not specified)
Location: torso *Form*: jacket	wearIT@work: motion jacket to support production and maintenance tasks (Stiefmeier et al., 2008)	*Computing*: no information *Sensors*: IMUs, force sensitive resistors, ultrawideband tags *UI*: none *Communication*: data bus, Bluetooth
Location: torso *Form*: suit	e-SUIT: business-suit-integrated control of an information management application (Toney et al., 2002)	*Computing*: microcontroller, StrongARM microprocessor *Sensors*: none *UI*: buttons, slide control, LEDs, LCD display, pager motor *Communication*: data bus, WLAN
Location: torso *Form*: underclothes	VTAMN: communicating underclothes for remote health monitoring (Noury et al., 2004)	*Computing*: no information *Sensors*: ECG, respiration rate monitor, temperature sensor, GPS *UI*: button *Communication*: I^2C, GSM
Location: torso *Form*: underclothes	MagIC: instrumented underclothes for remote health monitoring (Di Rienzo et al., 2005)	*Computing*: no information *Sensors*: ECG, respiration rate monitor, accelerometer *UI*: none *Communication*: RF transmission (not specified)
Location: torso *Form*: underclothes	WEALTHY: instrumented underclothes for remote health monitoring (Paradiso et al., 2008)	*Computing*: no information *Sensors*: ECG, respiration rate monitor (piezoresistive/impedance pneumography), piezoresistive elbow/shoulder joint movement monitor *UI*: buttons, LEDs, buzzer *Communication*: GPRS

(*Continued*)

TABLE 22.1 (*Continued*) Garment-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: torso, feet *Form*: shirt, jacket, and pair of boots	ProeTEX: smart garments for monitoring the health and environmental state of emergency-disaster personnel (Curone et al., 2010)	*Computing*: microcontroller *Sensors*: HR monitor, respiration rate monitor, temperature sensor, accelerometer, heat flux sensor, CO/CO_2 concentration, GPS *UI*: visual and acoustic alarm *Communication*: RS485 data bus, ZigBee, 802.11 WLAN
Location: arms and hands *Form*: glove	StrinGlove: data glove for sign language recognition (Kuroda et al., 2004)	*Computing*: DSP *Sensors*: bend sensors, contact sensors *UI*: none *Communication*: no information
Location: arms and hands *Form*: glove	Airwriting: glove-integrated system for 3D-handwriting recognition (Amma et al., 2013)	*Computing*: microcontroller *Sensors*: accelerometer, gyroscope *UI*: none *Communication*: Bluetooth
Location: legs *Form*: pair of pants	Instrumented pair of pants for monitoring lower extremity joints (Liu et al., 2008)	*Computing*: Atmel AVR Atmega8 microcontroller *Sensors*: accelerometers, gyroscopes, bend sensors *UI*: none *Communication*: I^2C, Bluetooth
Location: feet *Form*: shoes	Footnotes: instrumented shoes to manipulate real-time interactive musical outputs (Paradiso, 2002)	*Computing*: PIC 16C711 microcontroller *Sensors*: accelerometer, gyroscope, force sensitive resistor, bend sensor *UI*: none *Communication*: RF transmission (not specified)
Location: feet *Form*: shoes	Shoe-mouse: instrumented shoes as alternative (foot-controlled) input device (Ye et al., 2005)	*Computing*: Atmel AT90S8515 microcontroller *Sensors*: accelerometer, gyroscope, force sensitive resistor, bend sensor *UI*: none *Communication*: GPRS
Location: feet *Form*: shoes	GaitShoe: instrumented shoes for gait analysis (Bamberg et al., 2008)	*Computing*: C8051F206 microcontroller *Sensors*: accelerometer, gyroscope, force sensitive resistor, bend sensor, electric field sensor *UI*: none *Communication*: 916.50 MHz RF transmission (RF Monolithics DR3000-1)

(*Continued*)

TABLE 22.1 (*Continued*)
Garment-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: feet *Form*: bootee	Instrumented infant shoe for wireless pulse oximetry monitoring (Weber et al., 2007)	*Computing*: no information *Sensors*: pulse oximeter, accelerometer *UI*: none *Communication*: sub 1 GHz RF transmission (Nordic nRF9E5)

Remote health monitoring. In remote health monitoring, wearable computers often measure physiological parameters and activities of patients in their daily life. For example, Rosso et al. (2010) used a T-shirt to monitor physiological parameters, focusing on elderly patients with chronic diseases such as chronic obstructive pulmonary disease (COPD) and chronic kidney disease (CKD). A bootee-integrated system for monitoring infants was presented by Weber et al. (2007). Garment-based wearable computers were applied in the rehabilitation after medical treatment, for example, for cardiac and chronic respiration patients (Paradiso et al., 2008) and for applications in movement rehabilitation (Harms et al., 2008). Curone et al. (2010) equipped emergency-disaster personnel (e.g., firefighters, civil-protection authorities) with sensing and computing garments. Moreover, a few commercial products exist in this field, such as the LifeShirt system by VivoMetrics.*

Physical activity monitoring. Knight et al. (2005) described the design process of a vest-integrated system, used for monitoring school children's activities. Liu et al. (2008) used a pair of instrumented pants to assess the dynamic stability of motion-impaired elderly. Bamberg et al. (2008) presented an instrumented shoe for gait analysis outside of traditional motion analysis laboratories.

User interfaces. DeVaul et al. (2001) presented a wearable system called Memory Glasses, integrated in the lining of a zip-in vest, for context-aware reminder delivery. Toney et al. (2002) incorporated a wearable computer into a traditional business suit to control personal information management applications. An instrumented shoe was presented by Paradiso (2002) to manipulate real-time interactive musical outputs. Ye et al. (2005) described an alternative input using a shoe-based system for impaired people, who have difficulties using their hands for computer interaction. Kuroda et al. (2004) described a data glove used for sign language recognition.

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* http://vivonoetics.com/products/sensors/lifeshirt/.

Other applications. Further applications of garment-based wearable computers include sports (e.g., sensor shirts manufactured by Hexoskin[*] or different commercially available shoe-based systems). Motion monitoring was addressed for entertainment (e.g., the Xsens MVN[†]), and worker support during production and maintenance tasks, e.g., as a motion jacket (Stiefmeier et al., 2008). Cheng et al. (2010) presented a neck collar for dietary behavior monitoring.

Clearly, such a widespread collection of application scenarios defines different system requirements. Nevertheless, most garment-based wearable computers include the key components for sensing, computing, user interface, (wireless) data transmission, and power supply. Table 22.1 list all analyzed garment-based wearable computer projects. Detailed information on a system's architecture was not always available. For example, many projects mentioned computing units but did not provide details on memory or controller models. Power supply was omitted from the architecture overview as all projects reported to use batteries.

22.2.1 PLACEMENT ON HUMAN BODY

Most garment-based wearable computers in this analysis were placed on the torso. Typical garments worn on the torso and thus serving as basis of wearable systems include shirts, vests, jackets, and underclothes. Garment-form factors for other body areas include headbands, neckbands, gloves, wristlets, pants, and shoes. This section analyzes garment-based wearable computer projects optimized for placement at different body locations. Figure 22.1 summarizes all included projects and placements.

22.2.1.1 Head and Neck Region

Few projects for the head and neck region were found. Limited space, ergonomic considerations, and visibility may be the most challenging factors for wearable computers at the head and neck region. Kim et al. (2008) presented a headband to measure heart rate and accelerometer for step detection, including a pulse oximeter at the forehead, microcontroller for signal preprocessing, ZigBee module for wireless data transfer, and a rechargeable battery. Cheng et al. (2010) introduced capacitive textile electrodes in a neckband, attached microprocessor, and a ZigBee transceiver. As textile electrodes were used, an unobtrusive integration in scarfs, ties, or collars was considered.

22.2.1.2 Torso Region

Garments on the torso provide large substrate area and are centrally located regarding signaling distances and measurement requirements. Moreover, torso garments are close to the body's center of mass, thus supporting heavier system components such as batteries.

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[*] http://www.hexoskin.com/.

[†] http://www.xsens.com/products/xsens-mvn/.

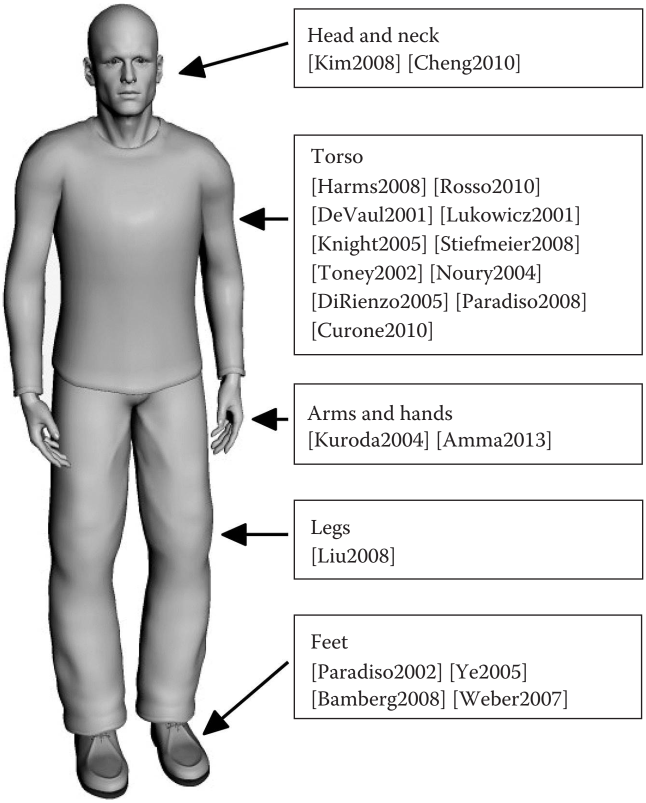

FIGURE 22.1 Garment-based wearable computer projects and their placement on the human body.

Wearable computers at the torso were typically distributed systems, utilizing waist, chest, back, or shoulders for components. Mostly, sensing at relevant body locations and main system components, such as batteries and computing, was separated. A prototypical example of a distributed torso-worn system was described by Harms et al. (2008). Their system was implemented into a loose-fitting long sleeve shirt, hence covering lower arms and the wrist locations too. The wearable computer design was hierarchical, consisting of a central master, region-specific gateways, and outer peripherals (terminals) that provide sensing and I/O functionality. Essential system components, including the master, gateways, and wiring, were glued onto the inner side of the garment, while a replaceable battery was placed in a pocket. Each gateway provided standardized interfaces to different terminals, such as accelerometer, buttons, and LEDs. Harms et al. (2008) position four gateways to maintain a balanced distribution of terminals over the entire body and limiting wiring stretches below 85 cm. Figure 22.2 shows an example shirt and the architecture schematic. Another shirt-based wearable system was presented by Rosso et al. (2010). They integrate a set of sensors (ECG electrodes, temperature sensors, accelerometers, etc.) into a T-shirt. In addition, an electronic module was attached to the T-shirt for data collection, analysis, and wireless transmission.

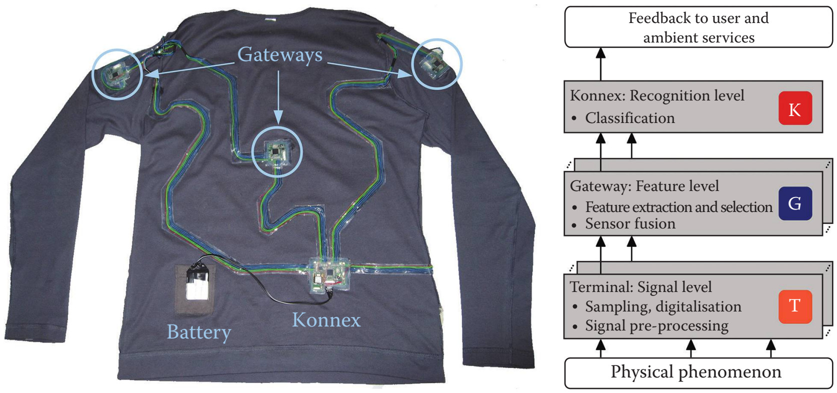

FIGURE 22.2 Example of garment-based wearable computer: SMASH shirt-integrated sensing and computing infrastructure and system schematic. (From Harms, H. et al., SMASH: A distributed sensing and processing garment for the classification of upper body postures, *Proceedings of Third International Conference on Body Area Networks* (*BodyNets*), ICST, Brussels, Belgium, 2008.)

Vest-based designs were preferred in many early wearable computer projects for practical reasons, with the vest's pockets used to carry bulky components. Moreover, shirt designs were found cumbersome during dressing and putting off (Knight et al., 2005). DeVaul et al. (2001) described the MIThril system, included in a chassis that acts as a lining in a zip-in vest. The MIThril architecture included two computing cores, a multi-protocol body bus, a range of I^2C-based sensors, and interface devices, such as clip-on HMD and Twiddler chording keyboard. Lukowicz et al. (2001) extend MIThril with a modular computing core called WearARM, supporting reconfigurable data processing and efficient power management. In Knight et al. (2005), vests were used to include sensors, core components, and output devices (LCD, LEDs). Similar to vest-based systems, jacket-based solutions allowed users fast dressing and stripping. Stiefmeier et al. (2008) described a motion jacket system, integrating inertial sensors and force-sensitive resistors together with processing and communication features. Toney et al. (2002) integrated components into a traditional business suit, including input and output interfaces connected to a PDA at the suit's inner pocket.

Underclothes were found particularly beneficial for physiological sensors that require direct skin contact. For example, Noury et al. (2004) developed a medical monitoring system integrated in an undercloth, including sensing components (such as ECG electrodes and temperature sensors), a fall detection module consisting of an accelerometer and a microcontroller, wiring and interconnection busses. In addition, the system included a belt, containing processing and communication components and batteries, wired to the garment. Di Rienzo et al. (2005) presented an undercloth-based system including textile sensors for ECG and respiration. Another undercloth-based wearable computer was presented by Paradiso et al. (2008). The garment, together with nine textile electrodes for cardiopulmonary monitoring, was realized in one knitting procedure. Sensors were connected to an electronics module, placed into a pocket at the lower back of cloth.

Curone et al. (2010) used three garment components: a T-shirt as inner garment, a jacket as outer garment, and a pair of boots. Each component was sensor-equipped for real-time monitoring of physiological, activity, and environmental parameters. The inner garment included textile sensors connected to an electronic module via textile conductive cables. The outer garment included additional sensors to measure, for example, external temperature, CO concentration, absolute position, and a processing module for collecting and preprocessing data from different sensor nodes. Moreover, electronic communication and alarm modules were attached for sending data to an operations coordinator and providing visual and acoustic warnings when dangerous situations were detected. The boots included CO_2 sensors and a ZigBee module.

22.2.1.3 Arms and Hands Region

While various glove-based devices were developed in the past years (cf. the survey of Dipietro et al., 2008), many of the related reports focus on information processing rather than integration (e.g., Park et al., 2008), and thus were not analyzed.

Kuroda et al. (2004) introduced a data glove, called StrinGlove integrating 24 bend sensors for hand posture monitoring and 9 contact sensors to detect contact between fingertips. Data processing was performed by a signal processor unit, mounted onto the glove. Amma et al. (2013) described a wearable computer in a thin glove and a wristlet. Their system consisted of a wireless data glove with inertial sensors at the hand's back, and microcontroller, Bluetooth module, and power supply at the wristlet. Besides the wearable computer, their system included an external module for intensive data processing tasks.

Some glove designs only included sensors or data input, such as hand tracking with a color glove (Wang and Popovic, 2009). Other glove-based projects are either commercial developments (e.g., the MoCap Glove from CyberGlove Systems[*] or data gloves from 5DT[†]) or rely on one of the available products. A few garment-based wearable computers for the torso covered upper limbs, too. For example, the long sleeve shirt of Harms et al. (2008) included terminals at upper and lower arms. Glove-like systems without fabric integration, as the SCURRY system (Kim et al., 2005), are covered as accessory in Section 22.3.

22.2.1.4 Legs Region

Liu et al. (2008) introduced trousers with printed circuit boards located at hips and leg joints, including inertial sensor, microcontroller with I^2C interface, and A/D converter. In addition, bend sensors were attached at the trousers' knee locations. In other projects, trousers were often used as part of a larger system for only sensing, thus are not discussed here.

22.2.1.5 Feet Region

Shoe-based wearable computers often included insole-integrated sensors, as well as an attached module with additional sensors and system components for data processing, communication, and power supply. Typically, only basic data processing, for

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[*] http://www.cyberglovesystems.com/.

[†] http://www.5dt.com/.

example, signal conditioning, was performed on the shoe wearable computer and then data was sent to an external system for further processing. Foot-mounted system designs were often constraint by space, required robust wear-resistant attachments, and autonomous operation to avoid wiring from foot/ankle to a trousers or waist-mounted computing unit, for example. The feet region was chosen in applications of gait analysis or for using feet as input device.

Using insole-sensors, dynamic pressure was frequently measured at the heel and great toe, as well as sole bending, for example, in Paradiso (2002). Bamberg et al. (2008) included a capacitive sensor in the insole to estimate foot height above floor level. Additional sensors, including accelerometers and gyroscopes were included in the shoe-attached module. Paradiso (2002) placed the shoe-attached module at shoe's side, Bamberg et al. (2008) used the shoe's back, while Ye et al. (2005) fully integrated the components inside the shoe. An infant shoe (bootee) for wireless monitoring of pulse oximetry was presented by Weber et al. (2007). Electronic components, including oximetry module, RF transceiver, and power supply, were contained in a box, integrated into a thick sole of the bootee.

22.3 ACCESSORY-BASED WEARABLE COMPUTERS

Application areas of accessory-based wearable computers largely overlap with those of garment-based systems. Examples of remote health monitoring applications include the continuous medical monitoring and alert system of Anliker et al. (2004) targeting high-risk cardiac and respiratory patients, and the multimodal physiological monitoring device of Malhi et al. (2012). With the e-AR ear-worn system, it was demonstrated how a similar design can be used for different applications: Wang et al. (2007) used the e-AR concept as a ubiquitous heart-rate monitoring device, while Jarchi et al. (2014) presented a gait analysis system. Examples of accessory-based wearable computers for user interaction were described by Tamaki et al. (2009) and Bulling et al. (2009). Kim et al. (2005) presented an input system named SCURRY used either as a wearable finger mouse or as a wearable keyboard.

A multifunctional wearable computer was presented in Amft et al. (2004), targeting medical aiding systems, mobile worker assistance, security and rescue applications, and sport exercise monitoring. The wearable autonomous microsystem of Bharatula et al. (2004) was intended for different context-awareness applications. Numerous applications were considered for smartwatches, from generic pager and activity trackers to information appliances. IBM's early wristwatch computer was developed for personal information management applications (Narayanaswami et al., 2002). The eWatch of Maurer et al. (2006) served as wearable sensor and notification platform, for example, for location recognition using audio and light sensor data. Wrist-worn devices are meanwhile widespread. A multitude of commercial smartwatches exist, including the Pebble[*] and Neptune Pine[†], that give access to

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[*] https://getpebble.com/.

[†] http://getneptune.com/.

internet-based services, gather data from other portable devices, or even serve as simple smartphone replacement.

Table 22.2 list accessory-based wearable computer projects analyzed and further discussed later per body region. While we aimed at extracting most architectural information from the projects' publications, often details were missing. The power supply was omitted from the architecture overview since most systems used batteries, except for solar cells in a sensor button system (Bharatula et al., 2004).

22.3.1 PLACEMENT ON HUMAN BODY

While the torso region was preferred for garment-based wearable computer projects, accessory-based systems were found preferably placed on the head, neck, and arms (cf. Figure 22.3). One important reason is that device size and weight does not exceed the perceived limits for these body regions. This section describes existing accessory-based wearable projects related to the different body areas.

22.3.1.1 Head and Neck Region

Ear-worn, hearing-aid-like devices are well suited as wearable computers integrated in accessories. The e-AR is a lightweight device (weights less than 10 g) that can be attached onto the ear. While e-AR was mostly considered without the full integration into an accessory, we included this project as a prototypical example as it provided insights into wearable computers in ear-worn accessories, such as earrings. e-AR included signal amplifiers, power supply, and wireless transceiver and an application-dependent sensing modality. Wang et al. (2007) used the e-AR system for reflective PPG measurement, thus embedding multiple LEDs and photodiodes into the device. Jarchi et al. (2014) integrated a three-axis accelerometer for gait analysis. Recently, our research group combined head measurement approaches in a regular eyeglasses design (Amft et al., 2015). Figure 22.4 illustrates the eyeglasses design.

Tamaki et al. (2009) presented the Brainy Hand system, an ear-worn single color camera for 3D hand gesture recognition, a laser line as a visual marker indicating the camera range, and an earphone for receiving audio feedback. Matsushita (2001) presented a head-mounted peripheral device, integrating two microcontrollers and further components into a headset. Microcontrollers were used for audio and inertial signal processing and connected via a 1 Mbps serial data bus integrated within the headset. Bulling et al. (2009) used goggles as accessory basis for their EOG-based eye tracker system consisting of dry electrodes attached via steel springs to the goggles. Amplification electronics, accelerometer sensor, and electrodes were wired to a processing and communication unit in an upper arm pocket.

22.3.1.2 Torso Region

Amft et al. (2004) presented a belt-integrated wearable computer called QBIC, where main system electronics running Linux had been integrated into the belt buckle, including microcontroller, memory, and wireless interfaces. The belt itself was used as extension bus and mechanical support for interfaces, consisting of two layers of leather with a flex-print wiring system in between. Belt interfaces included a head-mounted display connector, as well as RS232 and USB ports. The QBIC system was

TABLE 22.2
Accessory-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: head and neck *Form*: ear-worn device	e-AR: ear-worn activity and heart rate monitoring device (Jarchi et al., 2014)	*Computing*: Intel 8051 microcontroller *Sensors*: accelerometer, PPG *UI*: none *Communication*: 2.4 GHz RF transmission (Nordic nRF24E1)
Location: head and neck *Form*: ear-worn device	Brainy Hand: ear-worn interaction device based on hand gestures (Tamaki et al., 2009)	*Computing*: no information *Sensors*: camera *UI*: earphone, laser line *Communication*: no information
Location: head and neck *Form*: headset	Headset-based wearable computer for context-aware applications (Matsushita, 2001)	*Computing*: AT90S8515 microcontroller, PIC16LF877 microcontroller *Sensors*: accelerometer, gyroscope *UI*: speaker, microphone *Communication*: Bluetooth
Location: head and neck *Form*: goggles	EOG-based wearable eye tracking system (Bulling et al., 2009)	*Computing*: 16-bit dsPIC microcontroller (Microchip) *Sensors*: EOG, accelerometer, light sensor *UI*: none *Communication*: Bluetooth
Location: torso *Form*: belt	QBIC: belt-integrated wearable computing platform (Amft et al., 2004)	*Computing*: XScale microcontroller (Intel PXA263B1C400) *Sensors*: none *UI*: none *Communication*: USB, PS/2, VGA, RS-232, Bluetooth
Location: torso *Form*: button	Autonomous microsystem for context-aware applications (Bharatula et al., 2004)	*Computing*: CoolRisc 88 microcontroller *Sensors*: accelerometer, light sensor, microphone *UI*: none *Communication*: 868 MHz RF transmission
Location: arm *Form*: arm-band	MP3 player realized as a textile arm-band (Lee et al., 2010)	*Computing*: no information *Sensors*: none *UI*: buttons, LED array *Communication*: no information

(*Continued*)

TABLE 22.2 (*Continued*)
Accessory-Based Wearable Computer Projects Analyzed in This Review

Placement, Form Factor	Project, System Description, Application	Architecture Components
Location: wrist *Form*: watch	Linux Watch: smartwatch for e.g., personal information management applications (Narayanaswami et al., 2002)	*Computing*: ARM7 microcontroller (Cirrus Logic EP 7211) *Sensors*: none *UI*: OLED touch display, roller wheel *Communication*: Bluetooth, infrared
Location: wrist *Form*: watch	eWatch: smartwatch as a wearable sensing, notification, and computing platform (Maurer et al., 2006)	*Computing*: ARM7TDMI microcontroller (Philips LPC2106) *Sensors*: accelerometer, temperature sensor, light sensor, microphone *UI*: buttons, LCD display, buzzer, vibrating motor *Communication*: Bluetooth, infrared
Location: wrist *Form*: bracelet-like device	AMON: remote health monitoring and alert system (Anliker et al., 2004)	*Computing*: ARM7TDMI microcontroller (Atmel AT91R40807) *Sensors*: ECG, pulse oximeter, blood pressure system, accelerometer *UI*: buttons, LCD display *Communication*: GSM
Location: wrist *Form*: bracelet-like device	Remote health monitoring system (Malhi et al., 2012)	*Computing*: C8051F020 microcontroller *Sensors*: HR monitor, temperature sensor, accelerometer *UI*: none *Communication*: ZigBee
Location: hand and finger *Form*: glove-like device	SCURRY: hand-worn input device (Kim et al., 2005)	*Computing*: PIC microcontroller *Sensors*: accelerometers, gyroscopes *UI*: none *Communication*: 2.4 GHz RF transmission
Location: hand and finger *Form*: ring	Finger-worn device for remote health monitoring (Asada et al., 2003)	*Computing*: PIC microcontroller *Sensors*: PPG sensor *UI*: none *Communication*: 915 MHz RF transmission

used for different field studies, including daily routine monitoring and sports. The system is shown in Figure 22.5. Bharatula et al. (2004) presented a button concept as autonomous microsystem, integrated in a button-like form. Sensors for light, sound, and acceleration, microprocessor, and RF transceiver were included and a solar cell and lithium polymer battery was considered for powering. The button could replace regular buttons in cloths at various locations.

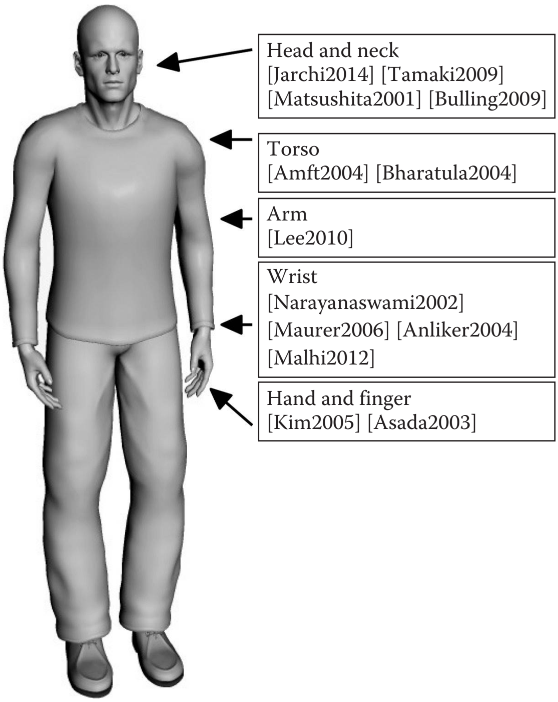

FIGURE 22.3 Accessory-based wearable computer projects and their placement on the human body.

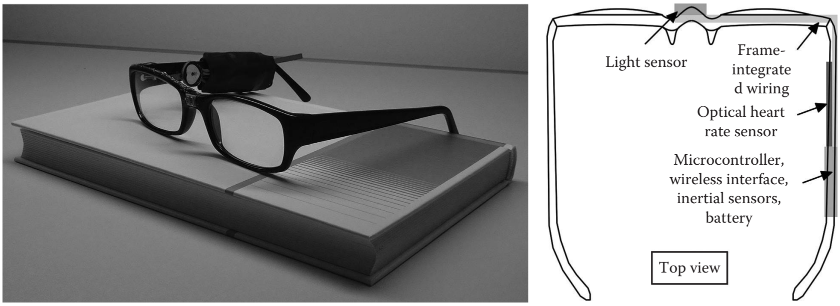

FIGURE 22.4 Example of an accessory-based wearable computer recently developed by our group. Various activity and physiology measurements were integrated into regular eyeglasses. (Amft et al., *IEEE Perv. Comput.*, 2015, in press).

22.3.1.3 Arm Region

Lee et al. (2010) presented an upper-arm-worn wearable computer, where the music player function was integrated in a textile using direct chip integration and implemented it as a sports armband. Two screen-printed layers of fabric patches were used. The first layer included a microcontroller, MP3 decoder, SD memory

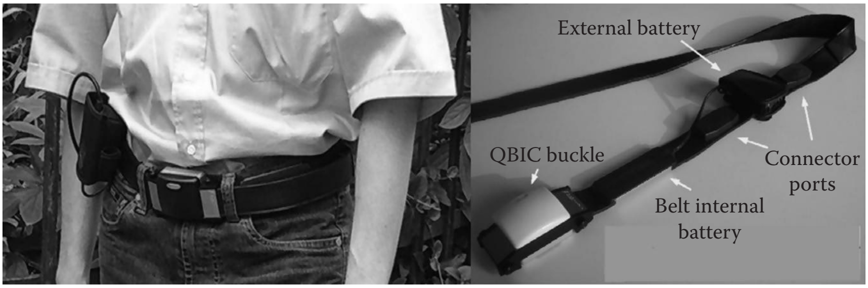

FIGURE 22.5 Example of accessory-based wearable computer: QBIC belt-integrated computer and system schematic. (From Amft, O. et al., Design of the QBIC wearable computing platform, *Proceedings of 15th IEEE International Conference on Application-Specific Systems, Architectures, and Processors* (*ASAP*), Galveston, TX, 2004, pp. 398–410.)

socket, and an earphone socket. The second layer was used to connect power and ground lines.

22.3.1.4 Wrist Region

Smartwatches are the predominant and commercially successful wearable computers at the wrist in recent years. Their success may be attributed to the reuse of an established accessory location: the user's wrist was used for watches in a long time. The location is easily accessible and considered for visual expressions of fashion or trendiness. Narayanaswami et al. (2002) introduced IBM Linux Watch, one of the earliest smartwatches. The Linux Watch was a complete computer running Linux, displaying X11 graphics, and had wireless connectivity. The system consisted of a main board with the processor, communications board including a Bluetooth module, and display board including an OLED display. Maurer et al. (2006) presented the eWatch device, a wearable sensing, notification, and computing platform built into a wrist watch–form factor. eWatch provided tactile, audio, and visual notification while monitoring light, motion, sound, and temperature. Beside sensors, user interface, and computing components, eWatch used Bluetooth to communicate with a cellphone or a stationary computer. Anliker et al. (2004) presented a bracelet-like device for continuous monitoring and evaluation of multiple physiological parameters, including blood pressure, ECG, and oxygen saturation. The enclosure included all sensors, processing and communication modules, power supply, and user interface. Medical emergency detection was performed at the device, and analyzed data was sent to a medical center unit. Another bracelet-based system is presented by Malhi et al. (2012), integrating sensors into the device to measure temperature, heart rate, and aim at detecting falls.

22.3.1.5 Hand and Finger Region

The human hand was as well considered for wearing accessory-based wearable computers. Kim et al. (2005) described a glove-like device called SCURRY, composed of a base module and four ring-type modules containing sensors, communication, and microcontroller components. The base module included two gyroscopes on the back of the hand, while the ring modules included two-axis accelerometers. Asada et al. (2003) considered a finger-worn ring accessory and integrated a PPG sensor, microcontroller for LED modulation, data acquisition, filtering, RF communication, and an RF transmitter. All components were encapsulated within the ring, in a compact body and powered by a tiny cell battery used for wristwatches.

22.3.1.6 Legs and Feet Region

No accessory-based wearable computers were found for the lower limbs region. Most wearable computer designs that aim for the lower limbs region are integrated into trousers or shoes, thus are considered in Sections 22.2.1.4 and 22.2.1.5.

22.4 LESSONS LEARNED AND BEST PRACTICES

Various technical challenges must be considered when designing and integrating garment-based and accessory-based wearable computers, including aspects related to safety, ergonomics, social acceptance, reliability, powering, and cost. In this section, technical challenges are discussed and lessons learned from the analyzed projects are summarized. We identified and categorized challenges based on (1) considerations from individual investigations found in the projects and (2) by grouping identified best practices. Table 22.3 provides an overview on lessons learned and best practices.

Most technical challenges can be directly linked to a seamless integration of wearable computers into daily life situations, where a user's outfit, system availability, and wearing comfort matters. Consequently, some best practices overlap between garment-based and accessory-based systems and are discussed here in parallel. Differences between the two variants mainly originate from garment-based systems being mostly distributed and placed on textile substrate, while accessory-based systems are encapsulated in small packages and placed at accessory locations of exposed body parts. Consequences of these differences will also be analyzed within this section. Most of the analyzed projects address some selected technical challenges, centered around wearability and sensor functions and neglecting cost and safety considerations. More extensive design and implementation reviews were gathered for garment-based systems by Toney et al. (2002), Knight et al. (2005), and Harms et al. (2008), and for accessory-based systems by Amft et al. (2004).

22.4.1 USER INTERFACE

As they are exposing a system's functionality with I/O modalities, user interfaces are key to user experience. Multifunctional wearable computers typically support a range of peripherals, including audio and visual, touch and keys, and buttons. Peripherals shall be easily accessible, interrupting users in suitable moments, yet being unobtrusive. DeVaul et al. (2001) stated that user interfaces shall maximize provided information value while minimizing physical and cognitive burdens imposed by accessing it.

TABLE 22.3
Technical Challenges of Wearable Computer Integration: Summary of Lessons Learned and Best Practices

Technical Challenge	Lessons Learned and Best Practice
User interface	• Buttons and touch interfaces are easily deployable input options in garments and require low cognitive load. • Multimodal controls and alternative options are deployed for information output, providing users with adequate feedback depending on the situation.
Sensing modalities	• Electrode-based physiological measurements can be replaced by conductive textile solutions using embroidery and knitting. Most physiological signals can be acquired in garments and accessories. • Current microsystems and sensors can be integrated in small accessories and garments. Errors in inertial and orientation estimates are expected when measuring at loose-fitting garments. • Sensor redundancy using multiple signal channels or sensing at different body locations can compensate low signal-noise ratio.
Data and power	• Sensors/peripherals in garments communicate to a central unit using low-bandwidth, low-power wired busses as commonly found in embedded systems, e.g., I^{2}C and SPI. • High-channel garment–electronics interfaces are necessary to realize detachable electronics.
Wearability	• Flexible components in garments should be flat and may consume relatively large surface area, but require similar properties than their fabric substrate, such as breathability and stretchability. • Rigid components should be placed on the trunk, at location of minimal shape change when moving, e.g., upper chest, upper back/shoulder region, and hips. Heaviest components may be placed near to the body's center of mass. • Textile electronics technology provides many solutions for integration, including textile electrodes, elongation sensors, wires, etc. • Accessory-based wearable computers need trade-off between sensor placement and signal quality, where wearability often directs to use placements with lower signal-to-noise ratio.
Social acceptance and aesthetics	• Providing usage options and system variants improves compatibility with different cloths and wearer preferences. • Aesthetic design can spur market success. Technology may be visible. • When systems cannot be invisibly integrated, providing indications of being unused, e.g., during conversations, may favor social acceptance.
Robustness and reliability	• Component protection from environmental stressors (heat, dust, liquid, etc.) is often accomplished by gluing components or detachable design. • Considerations are required to protect wiring and connectors to withstand long-term mechanical stress due to body motion, in both garment-based and accessory-based systems. • Selected materials shall have low toxicity, low chemical reactivity, and be thermally stable.

(*Continued*)

TABLE 22.3 (*Continued*)
Technical Challenges of Wearable Computer Integration: Summary of Lessons Learned and Best Practices

Technical Challenge	Lessons Learned and Best Practice
Extensibility	• Modular and hierarchical system architectures provide extensibility for multipurpose wearable computers, e.g., to add new sensors or peripherals, without modifying main system components.
Cost	• Off-the-shelf reusable components can minimize material cost. However, careful evaluations in the target environment are needed, when prior expertise and performance data is missing. • Market margins depend on business segments rather than functionality. In present consumer applications, wearable computers may add a small premium to the garment/accessory only.
Safety	• Minimize physical presence and cognitive load imposed by the system. Safe wiring, contact insulation, and skin-friendly material choice are essential. • Context awareness could be used to manage cognitive load. • Prototypes should be evaluated during long-term, realistic trials with nonexpert users.
On-body computing	• Distributed on-body processing reduces transmission and storage needs. Heterogeneous architectures, combining general-purpose and special-purpose subsystems could deal with application-specific processing needs. • Using a standard operating system expedites application development and abstracts hardware, e.g., of different application-specific implementations.

Toney et al. (2002) overlooked input options regarding cognitive load and external perception. Their investigations clearly favor garment-integrated hidden buttons as they do not lead to loss of eye contact in social situations when accessing them, and require limited cognitive load on the wearer. The authors implemented capacitive touch sensors by embroidered metal threads inside hems and cuffs of a suit jacket. The touch-sensitive buttons and sliders could be used to inconspicuously operate personal information management applications with common gestures when sitting and standing. Buttons with different design were frequently used in many other garment-based systems too (Paradiso et al., 2005; Harms et al., 2008; Lee et al., 2010). Textile-integrated buttons could be constructed via multilayer fabrics, for example, the MP3 player of Lee et al. (2010). As an example of more versatile wearable computers, the MIThril architecture supported various input devices, including audio via microphone and text entry via Twiddler and Palm folding keyboard.

While Maurer et al. (2006) used push buttons on their smartwatch. Narayanaswami et al. (2002) and others deliberately designed input interfaces without buttons, motivating this decision with ease of use and a more elegant appearance. The IBM Linux Watch included touch screen and a roller wheel. Due to the display size limits, only four quadrants with a potential fifth zone at the display's center were used. Instead, the roller wheel was used to navigate lists corresponding to a middle mouse wheel.

While among input options, touch and button interfaces dominate, a trend to multimodal output controls is observable for information feedback. Toney et al. (2002) investigated output options regarding cognitive load and external perception too and implemented LEDs in suit cuffs to inform on priority of available information. Furthermore, they considered a tactile feedback (pager motor) sewn into the jacket shoulder providing different vibration patterns, and a watch computer with a programmable LCD for short messages. Toney et al. (2002) considered that sound output required context information to enable it only when appropriate. In the scenario of Curone et al. (2010), garments included an alarm module for visual and acoustic warnings in emergencies. Moreover, user warnings are key in medical monitoring applications. LEDs and buzzers were used in various implementations to give immediate feedback (Paradiso et al., 2005; Harms et al., 2008). For physical activity monitoring, Knight et al. (2005) used LEDs indicating pulse measurements and an LCD display to show data.

In the eWatch, user notifications were displayed via a 128 × 64 pixel LCD display, LED, vibrating motor, and tone generating buzzer (Maurer et al., 2006). For the IBM Linux Watch, an OLED display was preferred over LCD for readability, reduced power consumption than backlit LCD, and for aesthetics. They chose yellow for the OLED due to higher contrast than blue or green. Narayanaswami et al. (2002) found no significant difference whether graphics were presented in landscape or portrait format, but, for example, for a phone book the landscape mode was preferred as fewer lines with more characters per line are easier to read. For particular applications, rather specific feedback options are however well conceivable. For example, Tamaki et al. (2009) used an earphone for audio feedback and a laser line/miniprojector to indicate the camera view in their ear-worn system.

22.4.2 SENSING MODALITIES

Sensor is a key asset of wearable computers that not only process direct user input but gather information from measurable phenomena. Various sensing modalities were integrated in garment-based and accessory-based wearable computers. Table 22.4 summarize signals, modalities, and integration approaches used in the included projects.

Sensors measuring physiological parameters were frequently found in underclothes as they require direct skin contact or skin proximity. Sensors to measure motion, activity, and environmental parameters could be placed on outer garments or accessories too, as long as a garment is tight-fitting (Harms et al., 2008). In garment-based systems, sensors were frequently attached (glued, sewn, fixed with Velcro straps) or integrated as yarn into the fabric itself, such as for textile electrodes. Since we review wearable computer projects, sensor modalities and integration techniques are certainly not exhaustive. Nevertheless, projects included here provide a useful summary on established sensing approaches.

Paradiso et al. (2005) knitted sensors in garments, including fabric ECG electrodes, using stainless-steel yarn, elongation sensors using piezoresistive yarns for respiration measurement as expansion and contraction of thoracic and abdomen regions, and for activity monitoring in sleeves. They used knitted electrodes at

TABLE 22.4
Overview of Sensing Modalities Found in the Wearable Computer Projects

Type of Signal	Sensing Approach	Type and Integration of Sensor
ECG, heart rate	ECG leads: precordial, Einthoven and Wilson	Conductive fabric electrodes are realized with knitting within underclothes[a,b]
ECG, heart rate	One-lead ECG with three electrodes	Gold electrodes are integrated into a wrist-worn device[c]
ECG, heart rate	Two electrodes at thorax level or four according to Einthoven	Conductive fabric electrodes are woven into underclothes[d,e,f]
Heart rate	Reflective PPG measured at finger/forehead/ear	PPG sensor integrated into finger ring[g]/headband[h]/earpiece[i]
Heart rate, blood oxygen saturation	Transmissive PPG measured at infant's foot	Pulse oximeter integrated into a bootee[j]
Blood oxygen saturation	Reflectance sensor placed on top of the wrist/next to the left vertebral ribs	Pulse oximeter integrated into a wrist-worn device[c]/attached to the internal side of a shirt[d]
Blood pressure	Standard oscillation method, the wrist and its vasculature are compressed	Encircling inflatable compression cuff (pump and valve) is integrated into a wrist-worn device[c]
Respiration rate, respiration volume	Inductive measurement of the abdomen and/or thorax volume displacement	Inductive coil(s) on the inside of an inner garment woven[d,e] or embroidered[f]
Respiration rate	Piezoresistive sensors at thoracic and abdomen location	Fabric piezoresistive sensors are realized with knitting within underclothes[a]
Respiration rate	Impedance pneumography: four electrodes placed at thoracic position	Conductive fabric electrodes are realized with knitting within underclothes[a]
Body temperature	Temperature probe (deduce core body temperature from the external temperature of the skin)	Temperature sensor placed at the armpit[d]/attached to a bracelet ensuring skin contact[k]
Blink detection, eye movement	EOG-based eye tracking	EOG electrodes are integrated into goggles[l]
Chewing and swallowing detection	Active capacitive sensing principle	Four conductive textile-based electrodes are sewed in between textile layers of a neckband[m]
Cough and snoring detection	Near-body audio signal analysis	Microphone placed externally onto a shirt, over the sternum[d]
Head movement	Active capacitive sensing principle	Four conductive textile-based electrodes are sewed in between textile layers of a neckband[m]
Upper body movement	Inertial measurement of each upper body part	IMUs are attached to a jacket[n]

(*Continued*)

TABLE 22.4 (*Continued*)
Overview of Sensing Modalities Found in the Wearable Computer Projects

Type of Signal	Sensing Approach	Type and Integration of Sensor
Elbow and shoulder joint movement	Piezoresistive sensors at elbow and shoulder joints	Fabric piezoresistive sensors are realized with knitting in the sleeves of underclothes[a]
Lower arm muscle activity	Detect muscle contraction with force-sensitive resistors (FSRs)	An array of FSRs is integrated into a strap, worn around the lower arm[n]
Hand and finger movement	Inertial measurement of hand and fingers	Accelerometers and gyroscopes integrated into a wrist-worn[o]/hand-worn device[p]
Finger flexure	Magnetic bend sensors	Bend sensors integrated into the fabric of a glove[q]
Detect contact between fingertips	Magnetic contact sensors	Magnetic coils integrated into the fabric of a glove[q]
Lower body movement	Inertial measurement of each lower body joint	Accelerometer/gyroscope sewed into pants at joints' location[r]
Knee bending	Piezoelectric bend strips	Piezoelectric bend sensors are sewed to the inside of pants at knee location[r]
Foot movement	Inertial measurement of the foot	Accelerometer/gyroscope attached to the shoe[s,t,u,v]
Dynamic pressure of the heel and toes	Force sensitive resistors in front of the shoe and under the heel	Piezoelectric strips are integrated within a shoe insole[t,u,v]
Flexion at the metatarsal-phalangeal joint	Bidirectional resistive bend sensor under the foot	Bend sensor is integrated within a shoe insole[t,u,v]
Plantar flexion and dorsiflexion	Vertical bidirectional resistive bend sensor at the back of the foot/ankle	Bend sensor is attached to the back of the shoe[t]
Overall body movement, fall detection, gait analysis	Measuring the torso/arm acceleration	Accelerometer attached to the body-worn computing unit,[w] placed over the sternum onto a shirt,[x] or integrated into a button[y]/earpiece[z]/wrist-worn device[aa]
Height of the foot above floor	Estimate the elevation of the foot via capacitive loading from the floor	Capacitive electric field sensor integrated into a shoe insole[t]
Relative position to an object	Place reference ultra-wideband transmitters around the object and tags on the wearer	Ultra-wideband tags are attached onto a jacket's shoulder region[ab]
Absolute position	GPS	GPS module attached to an outer garment[ac] or electronic module[ad]
Ambient temperature	Temperature probe	Temperature sensor placed on an outer garment[x,ac,ad]/integrated into a wrist-worn device[o]

(*Continued*)

TABLE 22.4 (*Continued*)
Overview of Sensing Modalities Found in the Wearable Computer Projects

Type of Signal	Sensing Approach	Type and Integration of Sensor
Ambient humidity	Humidity sensor	Humidity sensor placed externally onto a shirt[x]
Ambient light	Photodiode light sensor	Light sensor integrated into a wrist-worn device[o]/button[y]
Ambient sound	Microphone	Microphone integrated into a wrist-worn device[o]/button[y]
CO/CO_2 concentration	Using the potentiometric measuring principle	CO/CO_2 sensor attached to an outer garment[ac]

References: [a]Paradiso et al. (2005); [b]Paradiso et al. (2008); [c]Anliker et al. (2004); [d]Rosso et al. (2010); [e]Di Rienzo et al. (2005); [f]Noury et al. (2004); [g]Asada et al. (2003); [h]Kim et al. (2008); [i]Wang et al. (2007); [j]Weber et al. (2007); [k]Malhi et al. (2012); [l]Bulling et al. (2009); [m]Cheng et al. (2010); [n]Stiefmeier et al. (2008). [o]Maurer et al. (2006); [p]Kim et al. (2005); [q]Kuroda et al. (2004); [r]Liu et al. (2008); [s]Weber et al. (2007); [t]Bamberg et al. (2008); [u]Paradiso (2002); [v]Ye et al. (2005); [w]Di Rienzo et al. (2005); [x]Rosso et al. (2010); [y]Bharatula et al. (2004); [z]Jarchi et al. (2014); [aa]Anliker et al. (2004); [ab]Stiefmeier et al. (2008); [ac]Curone et al. (2010); [ad]Noury et al. (2004).

thoracic region for impedance pneumography too. Textile-woven ECG sensors from conductive fibers were integrated at thorax level in the vest of Di Rienzo et al. (2005). The vest included a textile transducer for measuring thorax volume changes, thus assessing respiratory frequency. Also Rosso et al. (2010) used textile electrodes but woven wires for inductive measurement of abdomen and thorax volume change. Cheng et al. (2010) deployed active capacitive sensing utilizing conductive textile electrodes to assess volume changes at the neck. They found that conductive fabrics are flexible and can be easily cut and sewed it into a neckband textile.

In accessories, ECG and respiration was often measured using dry electrodes. Anliker et al. (2004) integrated a one-lead ECG using three integrated gold electrodes, besides cuff-based blood pressure measurement in their wrist-worn system. Reflective pulse oximetry was implemented on the wrist top. In the ring wearable computer of Asada et al. (2003) reflective pulse oximetry was deployed, where the ring ensured a proper level of pressure and optically shielded the sensor unit. Rosso et al. (2010) placed the reflection sensor on the inner side of their T-shirt to measure oxygen saturation. Pulse measurements at fingertip or wrist are easily distorted by hand movement. Some projects considered alternative placements that may be considered comfortable and socially acceptable in particular applications, for example, headband to measure at the forehead (Kim et al., 2008). To measure body temperature, places on a garment's inside (Rosso et al., 2010) and in a bracelet (Malhi et al., 2012) were considered. Skin temperature at the wrist is affected by environmental conditions, however, such that a correlation with the core body temperature is rather low (Anliker et al., 2004). Bulling et al. (2009) measured the EOG with dry electrodes integrated into a goggles frame and compensated motion artifacts using an accelerometer.

Inertial sensors are widely used to monitor physical activity in garment-based and accessory-based systems. Examples include step and fall detection (Kim et al., 2008; Rosso et al., 2010), upper body posture and motion capture (Harms et al., 2008; Stiefmeier et al., 2008), finger motion (Kim et al., 2005), and physical activity monitoring (Anliker et al., 2004). Besides inertial sensors, shoe-based wearable systems typically include pressure and bend sensors, directly integrated into insoles, such as piezoelectric strips (Paradiso, 2002; Bamberg et al., 2008), bidirectional bend and capacitive sensors (Bamberg et al., 2008). Additional sensor modalities found in wearable computers include GPS and CO and CO_2 concentration (Curone et al., 2010), ultrawideband radar (Stiefmeier et al., 2008), and ambient temperature and humidity (Rosso et al., 2010).

22.4.3 Data and Power

In garment-based wearable computers, communication of sensors or peripheral to a central computing unit was often accomplished using low-bandwidth and low-power connections commonly found in embedded systems, as the two-line I^2C bus. I^2C is extensible regarding communicating nodes (Noury et al., 2004) and addition of custom nodes (DeVaul et al., 2001). Alternatives include other typical embedded systems busses as the four-wire SPI. Harms et al. (2008) connected components via an SPI, in a redundant star topology to compensate line breakages in the textile. Curone et al. (2010) used RS485 to connect components in inner and outer garment to a central master and to distribute power. While USB provides higher bandwidth, it is more complex to implement, thus remains an option for multipurpose wearable computers connecting off-the-shelf components, such as USB cameras, drives, or microphones as in the QBIC system (Amft et al., 2004). Wireless communication was used to transmit data from the wearable system to remote processing units, where necessary. Most common protocols are Bluetooth (Amma et al., 2013) and ZigBee (Kim et al., 2008).

Combined data and power distribution provide efficient system solutions, as for example, using RS485 bus (Curone et al., 2010). Multipurpose wearable computer implementations often provide dedicated data and power infrastructure. Amft et al. (2004) integrated data and power lines in a flex-print inside the belt of the QBIC system. Peripherals could access the lines at different connection points. The MIThril body bus (DeVaul et al., 2001) used a branching single-connection power/data bus. While early garment-based wearable systems distributed data and power via cables routed on the textile and fixed, for example, by Velcro straps, more recent garments use fabric-integrated wiring, for example, by embroidery (Noury et al., 2004). Lee et al. (2010) realized power and ground lines as separate layers. Recently, the development of textile-electronics connectors has gained interest, as more data lines need to be connected. For example, Curone et al. (2010) used nine-pin and four-pin connectors, both composed of a washable garment-integrated and a nonwashable electronics attachment part.

22.4.4 WEARABILITY

Wearability and ergonomics have been key challenges since the first wearable computers, involving system size, shape, and weight (Gemperle et al., 1998; Knight and Deen-Williams, 2006). Wearing a garment-based or accessory-based wearable computer shall not alter the usual perception of a garment or accessory, nor the wearer's usual posture and movement. Comfortable wearing, easy setup, and maintenance are concurrent requirements. Ideally, a user attaches the system on in the morning, takes it off in the evening, and completely forgets about it in between except when actively using its functionality (DeVaul et al., 2001).

Knight et al. (2005) suggested that anthropometric data should be considered and gathered design choices for smart garments: (1) components shall be flat but may consume relatively large surface area (cf. recommendations of Gemperle et al., 1998) and (2) components should be located on the trunk at location of minimal shape change when bending or moving. According to Knight et al. (2005), appropriate body regions include upper chest, upper back shoulder region, and hips. They reported that their initial shirt design was impractical during dressing and stripping, and thus changed to a vest design that closes on the chest. Bharatula et al. (2004) suggested that body areas often in contact with objects, for example, underside of arms and hands, back, bottom, and feet, should only contain seamless integrated components within the fabric's thickness. In a similar gist, Paradiso (2002) noted that at the shoe's outer side, components can be placed without constraining common movement. Textile electrodes, elongation sensors, and other embroidered or knitted transducers, wires, etc., are suitable components for comfortable wearable computers; however, textile components require similar properties than their fabric substrate, such as breathability and stretchability.

Functional yarns have been integrated into the fabric structure of garment-based systems, for example, to acquire ECG and respiration. However, garments cannot be entirely constructed from conductive fabric as conductive region may be too rigid and uncomfortable. Hence metal threads are usually twisted around standard textile yarn. The amount of metal in a fabric is a compromise between required electrical properties and the necessity to maintain mechanical behavior compatible with textile applications (Paradiso and Pacelli, 2011). Lukowicz et al. (2001) targeted a garment to be soft on the inside for comfortable wear, and rigid on the outside for robustness, for example, to protect system components. They experimented with different material combinations. However, soft fabric garments may be difficult to attach and take off, as they do not maintain shape and hold sensors (Kuroda et al., 2004).

Compared to garment-based wearable computers, miniaturization and integration of wearable computers in common accessories still appear as open challenges. Current projects often made trade-offs toward a wearable design. Anliker et al. (2004) integrated various vital monitoring functions into their wrist-worn AMON system, thus easing an integration in everyday life activities. However, this *all-in-one* design disfavors optimal sensor positioning. For example, acquiring ECG became a hard challenge for the AMON system, compared to chest-worn solutions. A trade-off between wearability and signal quality is frequently found in wearable computers. For example, in EOG goggles, signal amplification and A/D conversion is ideally performed at the electrodes, while weight and size considerations resulted in wiring EOG electrodes to an upper arm processing unit. Due to longer wires, analog high-impedance EOG signals pick up an increased amount of noise (Bulling et al., 2009).

The ring-based system of Asada et al. (2003) impressively shows miniaturization; however, it still remains larger than typical finger rings. Besides size, weight remains a critical design consideration. DeVaul et al. (2001) report a total weight of ~2 kg for the MIThril system. They addressed weight distribution using a zip-in vest design that balanced weight between shoulders. While overall system size decreased in recent systems, weight is determined by powering needs, hence the battery. Noury et al. (2004) placed larger and heavier system components, including battery, computing and communication units, separately from the garment on a belt. Amft et al. (2004) used the belt to integrate the complete wearable computer, weighting ~350 g. Matsushita's (2001) headset system weighted 220 g and the system of Bulling et al. (2009) was 188 g, with the goggles weighting only 60 g. To minimize energy needs, dynamic context-aware power management appears to be an important topic for further research.

22.4.5 SOCIAL ACCEPTANCE AND AESTHETICS

Aesthetically pleasant design may be key to the consumer market success of accessory-based wearable computers, as demonstrated by recent commercial smartwatches. Similar features may help garment-based systems to become successful too, by hiding privacy-sensitive and technical details, such as alarm buttons and electrodes, but promoting comfort and commodity functions.

The overall objective for wearable computer aesthetics is a seamless integration of all system components with the wearer's everyday outfit. For example, DeVaul et al. (2001) present a zip-in vest design that is compatible with a wide range of outer wear options, from shirts to suits. Amft et al. (2004) create a variety of belts with different color and texture; the buckle can be taken off from the belt and transferred between different belt types. Knight et al. (2005) prefer a vest over a shirt, since a longer vest provided social comfort to the wearer. They further used zippers instead of Velcro straps to avoid gaps when closing the vest.

Alternative integration strategies, alleviating fashion and taste-dependent design considerations, may be to integrate garment-based systems in underclothes (Noury et al., 2004). By contrast, accessory-based systems, such as wrist watches (Maurer et al., 2006) or finger rings (Asada et al., 2003), are continuously exposed and are therefore substantially affected by aesthetic considerations.

Social acceptance of wearable computers clearly addresses factors beyond physical presence. Toney et al. (2002) describe a social weight of an item or technology as: "the measure of the degradation of social interaction that occurs between the user and other people caused by the use of that item or technology." Evidently, a piece of technology that is not noticeable to other people has an inherent low social weight. Wearable computers that incur social weight could provide indications of being unused during social interactions, that is, to avoid distracting conversation partners. Further factors such as technology apprehension or cognitive load induced by interacting with the wearable system should be considered as well when designing wearable computers (Toney et al., 2002).

22.4.6 ROBUSTNESS AND RELIABILITY

As part of a user's everyday outfit, wearable computers are exposed to severe stress, including different environmental conditions, moisture, sweat, cleaning, and activity-related mechanical stress and vibrations. These stressors affect both garment-based and accessory-based systems.

An established strategy is to design sensitive electronic units to be removable from garments. For example, Paradiso et al. (2008) made underclothes washable by detaching the portable patient unit. Cleaning is simplified when using recent textile conductive sensors. Di Rienzo et al. (2005) developed a fully washable vest. Harms et al. (2008) glued components onto their SMASH shirt's inside, to sustain wearing and cleaning. They use silicone gel for gluing, which has various benefits for garment-based systems: low toxicity, electrically insulating, thermally stable, and low chemical reactivity (resistant to oxygen and ozone). Figure 22.6 illustrates steps for integrating electronics in the SMASH shirt. Rigid areas improved component protection in clothing (Lukowicz et al., 2001). Knight et al. (2005) used 100% polyester twill for their vest, chosen for its strength, durability, and ease of washing. Moreover, they use nylon webbing for required straps, due to strength and nonslip characteristics.

Accessory-based systems require similar robustness considerations. In the QBIC mechanical design, Amft et al. (2004) used a tight buckle closing and sealed housings to prevent dust or liquid reaching electronic components. To withstand strong forces, the belt side of the buckle consists of a stainless steel section.

Wiring and connectors should be specifically considered and suitable methods are chosen, for example, for strain relief, contact sealing, and parts reliability assessment. In particular, as garments and accessories are constantly flexing during use, continuous mechanical stress could cause rapid fatigue and thus lead to failures. DeVaul et al. (2001) reported that a complete re-engineering of their body-bus system was necessary due to connector failure after less than a year of use. The QBIC system (Amft et al., 2004) was used in various daily routine and sports monitoring studies. The flex-print belt connections to the buckle showed cracks in signal lines after only a few weeks of use and thus needed continuous replacement and repair.

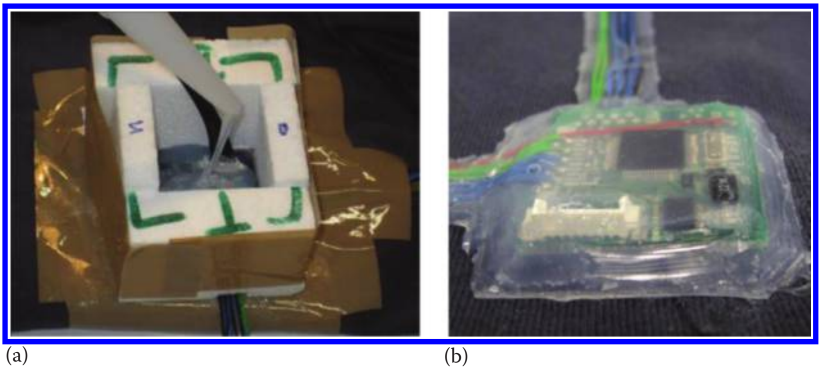
(a) (b)

FIGURE 22.6 Example of integration process using silicone depositing (a) and final result (b) of the SMASH shirt. (Images courtesy of Holger Harms.)

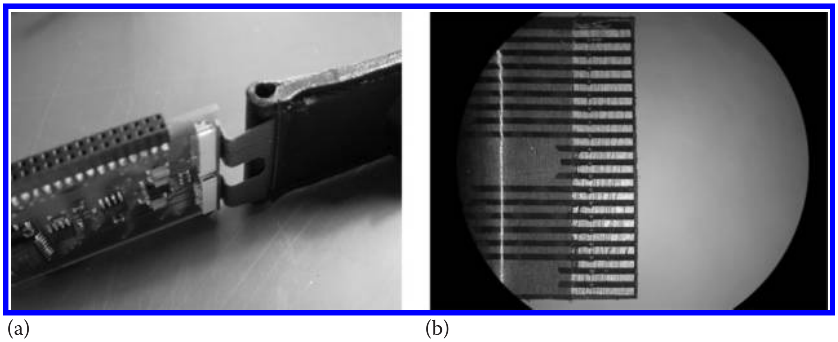
(a) (b)

FIGURE 22.7 Example of wearout effects due to mechanical and chemical stress in the flex-print (a) and connector (b) of the QBIC belt computer. (Private images of the authors.)

Figure 22.7 shows examples of the line cracks leading to data and power connection failures. The connectors were subsequently tinned to reduce the effect.

Foot-worn systems are particularly affected by mechanical stress due to foot impact shocks and high accelerations during movement, requiring components to be well attached or latched down. Paradiso (2002) covered the electronics board with a protective Plexiglas shield. Sensors placed in insoles should be protected from abrasion, moisture, etc., which can be addressed by sealing and placing sensor insoles beneath a regular insole in shoes (Paradiso, 2002).

22.4.7 EXTENSIBILITY

Aiming at multipurpose wearable computers, DeVaul et al. (2001) suggested that systems should support the widest range of users and applications, which require physical and functional reconfiguration options by design. In many projects, the system design was optimized for a particular purpose, hence reducing the need for extensibility. For multipurpose garment-based systems, extensibility primarily addresses adding further electronic components. Reconfiguration of the textile-integrated functions was not sufficiently considered, seemingly due to missing base-fabric technology.

The garment designs of Harms et al. (2008) and Curone et al. (2010) follow a modular architecture, where extensions such as adding sensors do not require modifying the central computing module. The vest design of Knight et al. (2005) included two originally unused pockets, intended to house future additions. Harms et al. (2008) deployed a hierarchical architecture consisting of three layers: terminals, gateways, and central master, where gateways provide interfaces for sensors and peripherals. Hubs could extend terminal count at a gateway to 127; thus the system can be equipped with ~500 terminals in total.

Among the accessory-based wearable computers, Amft et al. (2004) addressed extensibility by providing access to the QBIC system bus inside the belt for additional peripheral devices. In addition, the buckle contained main and extension boards. The latter included peripheral and wireless interfaces that could be replaced depending on the application and a specific belt configuration.

22.4.8 COST

Except for smartwatches and activity trackers, current garment-based and accessory-based wearable computers must yet be seen as niche products. Market price, and hence production cost, is a key concern for adoption, in particular for mass market garment and accessory products. Among the included projects, only few considered cost aspects. A common approach was to build on components of the shelf only and minimizing total component count.

Toney et al. (2002) estimated that their suit could be mass-produced at $17–$20 for the integrated electronics. Wearable computers provide a rich design space to choose implementation options for cost-sensitive designs; however, they require dedicated component evaluations in the targeted environment or application when prior experience and performance data are missing. For example, Knight et al. (2005) considered several alternatives for heart-rate monitoring and selected an insert microphone and pressure bulb as these were the cheapest options. However, components needed to be replaced with more expensive alternatives due to motion artifact sensitivity.

Current garment-based wearable computers are frequently found in niches, where higher market prices can be established. One main issue is the special production process required for textile-integrated components. Accessory-based systems may be less affected by production and technology-related risks, which enabled vendors to successfully promote smartwatches.

22.4.9 SAFETY

As new functionality is added, wearable computers are disruptive to classical uses of garments and accessories. While reported cases of accidents while wearing custom wearable computers exist, for example DeVaul et al. (2001), current safety considerations are premature. Since wearable computers include electronic modules, wiring, batteries, etc., fundamental electrical safety considerations shall be applied and possibly extended for the needs of wearable systems in the future.

Key factors affecting safety include physical presence of the system, and cognitive load imposed on the wearer. Bulky and rigid design affects physical presence and should be avoided. Similarly, wiring inside the outfit and contact insulation are essential for safe handling and to prevent failures. For example, Knight et al. (2005) sewed wire channels into their vest to pass leads through. Matsushita (2001) lowered Bluetooth radio power of their headset system to reduce microwave irradiation into the user's head.

Cognitive load is best addressed by user interfaces that minimize disruptive interrupts and attention during operation. Interruption moments could be determined from user context information processing. To further eliminate safety concerns, wearable system prototypes and their user interfaces should be evaluated during long-term realistic trials with nonexperts wearing the system in their daily routine.

22.4.10 ON-BODY COMPUTING

In the headset-based system of Matsushita (2001), step detection was directly performed on the system. The AMON wrist-worn device analyzed measurements online, including signal filtering and converting measured values into medical values, for example, for blood pressure and RR distance, and performing automated evaluations for emergency detection (Anliker et al., 2004). The QBIC system was used to run the CRNT streaming framework to recognize various activities (Bannach et al., 2008). Rosso et al. (2010) used decision-tree algorithms on a PDA attached to their sensor-embedded T-shirt to recognize worsening condition and provide immediate wearer feedback, while computationally intensive algorithms were executed remotely. Curone et al. (2010) distributed signal processing and information extraction at sensor level in their outer garment.

Distributed processing and information extraction in wearable computers reduces overall computational complexity and data amount to be communicated. Lukowicz et al. (2001) observed that many computationally intensive tasks are application-specific, for example, signal or image processing, and general-purpose processors are not optimally suited. Their WearARM design consisted of a heterogeneous, distributed architecture with general-purpose and special-purpose subsystems. The latter included low-power DSPs to perform computations using a fraction of a general-purpose processor's time. Harms et al. (2008) distributed tasks onto a hierarchical network of different garment-integrated nodes. Terminals were equipped with an 8-bit microprocessor for sensor signal preprocessing and translation. Subsequently, gateways equipped with a 16-bit microcontroller concentrated data from several attached terminals and extracted features. Eventually, a central master unit processed feature data for online classification using a nearest centroid classifier on a 16-bit microcontroller.

Few accessory-based wearable computers used operating systems to expedite application development, abstract hardware, and use existing libraries and data processing frameworks. Both, IBM's smartwatch and the QBIC belt system ran GNU/Linux. The EOG goggles ran freeRTOS. For garment-based wearable computers, design and implementation of a dedicated operating system, called GarmentOS, was proposed by Cheng et al. (2013).

22.5 FUTURE DIRECTIONS IN WEARABLE COMPUTING

Over the past 30 years, wearable computer technology has made profound progress, resulting in recent market successes. While the introduction of smartphones could be considered as a game-changing breakthrough for wearable computers, it primarily helped progressing in individual technical challenges, including sensing, user interface, and on-body computing. Our review concentrated on projects aiming at integrating electronics in functional garments and accessories, hence to assess progress toward the invisible computing paradigm for wearable systems. This section summarizes conclusions and future research directions in wearable computing.

Market potential and sustainability. Current commercial wearable devices, including smartwatches and activity trackers show low sustainability. According to a 2014 Endeavour Partners report[*] one-third of American

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[*] http://endeavourpartners.net/white-papers/.

consumers who have owned a wearable product stopped using it within 6 months. Attributed reasons include missing actionable feedback for users. While many systems illustrate measurement data, concrete lifestyle-related recommendations are lacking. A more fundamental reason for lacking success may be that thorough validation and performance reporting of many marketed devices do not exist. Robust evaluation standards are needed against which wearable systems can be tested and the reports should be made publicly accessible. Based on device performance data, relevant feedback and actuation could be designed for both novel garment-based and accessory-based wearable computers.

Garment-based wearable computers. The application field for garment-based systems is cluttered with many highly specialized designs and functionality to address individual niches. However, individual applications lack the volume for textile mass production and hence incur high manufacturing cost. One central approach investigated by the recent European project SimpleSkin* is to standardize textile functionality similar to general purpose electronics and reconfigure textile functions via software. The concept builds on an operating system for garments, called GarmentOS (Cheng et al., 2013), to provide a hardware abstraction for application developers similar to that of smartphone apps. Such garment apps are considered to reconfigure many components of the wearable computer, including the textile sensing functions, data communication, and others. If successful, the approach could enable textile manufacturers to mass-produce fabric that suits for many applications of garment-based wearable computers.

Accessory-based wearable computers. As our analysis showed, integrating wearable computers in real-life accessories is particularly challenging due to space constraints and miniaturization involving electronics and power supply. For devices such as rings, necklaces, etc., standard electronic components may still be too large to obtain perfect integration. Due to the persisting limitations in integrating accessory-based systems, stick-on devices, including skin-attached plasters may take further momentum. For example, MC10† markets first stick-on sensor plasters for physiological monitoring.

User interaction. Currently, button and touch interfaces are predominant interaction and control approaches for wearable computing. Minimizing the cognitive burden of a context switch (from/to interacting with the wearable computer) remains a challenge. As Google Glass and similar developments show, processing context information can help to identify relevant information as well as sensible moments to interrupt users.

Sensing and on-body computing. While performance of textile-integrated sensors gradually improves, the fundamental limitation remains that wearable computers obtain noisy measurements due to imperfect sensor placement or measurement conditions. Recent works have shown that adding sensor channels and modalities increases available information and potential

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* http://www.simpleskin.org.

† http://www.mc10inc.com.

for artifact compensation. Wearable computers provide the necessary processing resources for novel artifact handling algorithms. Future wearable computers require more elaborate context analysis functionality to differentiate customer offerings and increase user value.

Power management. Our review has shown that current wearable computers generally rely on rechargeable batteries. As energy harvesting solutions are taking momentum, future developments may combine batteries and harvesters to extend battery lifetime. However, further development of harvesting solutions is needed to eventually power wearable computers continuously. Wearable computer power consumption could be reduced by context-aware dynamic power management, that is, to scale computing, peripherals, and sensor needs according to the present situation and trends.

Wearability, extensibility, cost. Evaluating wearable computer systems is still a time and effort-intensive undertaking. Development costs may rise due to lacking prior performance data for a given device and a particular application. Novel rapid prototyping approaches are needed to expedite the evaluation process. Recent work on joint sensor and garment simulation can provide estimations before actually implementing systems (Harms et al., 2012).

Robustness and safety. For accessory-based systems, sealing devices can minimize chemical stress, and elaborate mechanical design can help to deal with forces during everyday use. For garment-based systems, continuous wearing and cleaning cycles remain a critical issue. Detachable electronics can mitigate cost implications of more frequent garment replacements; however, these require robust dense-channel connectors in the garment. Future research in connection technology is needed to find and standardize connector designs. Similarly, safety standards still need to be established for wearable computers that include handling instructions on how to operate garment and electronics.

Social acceptance and aesthetics. While the overall acceptance for body-worn technology has increased in recent years, wearable computers are still not established as part of our daily outfit. With the continuous progress made, it seems conceivable that real wearable computers enter evaluation stages within the next years and thus continue the momentum created by current carry-on and stick-on devices.

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