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Review

The Agenda of Wearable Healthcare

Abstract: Driven by cost and quality issues, the health system in the developed countries will undergo a fundamental change in this decade, from a physician-operated and hospital centred health system to consumer operated personal prevention, early risk detection and wellness system. This paper sketches the vision of a 'Personal Health Assistant' PHA, opening up new vistas in patient centred healthcare. The PHA comprises a wearable sensing and communicating system, seamlessly embedded in our daily outfit. Several on-body sensors identify the biometric and contextual status of the wearer continuously. The embedded computer generates the 'Life Balance Factor' LBF as an individual feedback to the user and to the surroundings affording an effective prevention, disease management and rehabilitation also in telemedicine. The state-of-the-art enabling technologies – mainly miniaturization of electronics and sensors combined with wireless communication – and recent developments in wearable and pervasive computing are presented and assessed concerning multiparameter health monitoring.

1. From Mainframe Healthcare to the Personal Health Assistant PHA?

As a global trend, healthcare related costs create an increasing pressure on the economies in the developed countries: In 2002, for example, the US Americans and the Germans expended about 13 percent of their national income for healthcare [1]. Considering the demographic development, an increase to 20 percent in 2025 is expected. The elderly population over age 65 will increase almost twice as fast as the rest of the population, whereas the percentage of the population under age 65 declines [2].

With the longevity also the age-related disabilities and diseases are rising. Mainly because of the hospital costs, a German seventy-year-old patient costs five times more than a twenty-year-old patient. As another example, the US Alzheimer Association calculated an increase of annual cost to businesses caused by

Alzheimer's disease from \$ 33 billion in 1998 to \$ 61 billion in 2002 [3]. In addition to the demographic pressure, people expect continuously high quality in healthcare, through the access to improved medical therapies, drugs or home care. The fact that the ratio of workers to retirees will drop to 2:1 [4] will impose increasing pressure upon the social security systems.

These figures should briefly illustrate that the health systems in the developed countries have to change radically in the near future, driven by quality and cost issues [5].

Andy Grove, Intel's legendary founder, has characterized the current situation of healthcare by the metaphor of mainframe computers, the dominating systems in the sixties [2]: few, expensive powerful machines, localized in a dedicated environment and operated by skilled specialists acting as interface between the user and the computer. Personal computer in the eighties and mobile phones and PDAs in the nineties have outstripped

mainframes in quantity and performance. Could we imagine a similar trend, from mainframe healthcare to a personal health assistant PHA?

Recent developments in micro- and nanotechnology, low power computing, and wireless communication as well as in information processing have paved the way to non-invasive and mobile biomedical measurements and health monitoring [6] providing the technological platform for the PHA.

A scenario may help to sketch the potentials of these emerging technologies. As described later in this paper, manifold smart miniaturized sensors, connected by a wireless or wired body area network to data processing and communication devices will be embedded in our daily outfit. This wearable personal health assistant (PHA) monitors continuously the wearer's vital signs like heart rate, heart rate variability, temperature and motion activities. The combination of vital parameters with the wearer's context, the activity and sleep patterns, social interactions

and other health indicators paint a picture of the physiological state. To facilitate the interface between the PHA and the individual user we propose a 'Life Balance Factor' LBF as a plain health measure and generally understandable indicator, especially designed for medical laypersons. The LBF summarizes the current physiological state; it indicates health changes and calls on a consultation if health parameters are moving to a critical range.

People becoming more 'health conscious' are interested in that feedback as well as in better health and life style management, including rehabilitation, fitness, sport etc [6]. Moreover, this 'healthwear' [7] - enabled by the PHA - opens the opportunity to reduce healthcare costs by avoiding unnecessary hospitalization for the aged and chronically ill people.

The technological challenges in designing the PHA and the attractive economical prognosis have initiated manifold research efforts e.g. in the US by NSF¹ as well as by the European Commission²; the list³ summarizes the ongoing projects in the 6th EU Framework Programme.

Organization: This paper aims at a survey on wearable computing technology and its potentials for healthcare applications. After a walk-through of the terminologies and examples of wearable computing, we investigate the existing technologies to monitor vital parameters in a mobile environment. Then we address some scenarios and applications in diagnosis as well as in prevention.

2. The Concept of Wearable Computing

1. History

Understanding wearable systems as devices that we put on daily and which should improve our abilities, the first mention of eyeglasses in 1268 could be stated as the birth of wearable systems. [8]. The inventions of the pocket-watch in 1762, and of the wristwatch in 1907 mark the trend to miniaturized and mobile components. As a next milestone, the patent of a head-mounted stereophonic television display was filled in 1960. With the HP01 algebraic calculator watch, released by Hewlett-Packard in 1977, the first miniaturized mobile computer was commercialized. Then the appearance of the microprocessor has accelerated the development. Steve Mann, a pioneer in wearable computing, designed a backpack-mounted computer with a camera and a display in 1981. Olivetti presented an active badge system in 1990, equipped with an infrared device to communicate a person's location. In 1991, students at Carnegie Mellon's Engineering Design Research Center developed the VuMan 1, a wearable computer worn on the belt and powered by an 8 MHz 80188 processor with 0.5 MB ROM [9]. The VuMan concept has been refined in a series of wearable systems. DARPA⁴ sponsored the 'Smart Module Program' in 1994, and in 1996, the 'Wearable 2005' workshop. Then Boeing hosted a wearable conference also in 1996, before in 1997 the first IEEE International Sym-

posium on Wearable Computers took place in Cambridge, MA. The attendance of 380 people at this symposium has indicated the emerging interest in academia. Also the growing number of scientific publications confirms the trend; for example, INSPEC, the bibliographic database⁵ has registered a constant growth from 3 publications in 1996 to 75 publications in 2000. Worldwide more than 25 research labs in academy and industry have initiated wearable computing projects⁶. After 15 years of research and development, wearable computers will gain commercial relevance soon. In 2006 VDC (Venture Development Corporation⁷) sees a worldwide shipment of Wearable Computer between \$ 550 millions and \$1 billion with a compound annual growth rate (CAGR) of 50 percent.

In healthcare, hearing aids or cardiac pacemaker mark one of the first wearable systems. Non-electric hearing aids in form of an ear trumpet were already fabricated in the 1800's. Then the first electric hearing aids occurred in the early 1900's, initially equipped with vacuum tubes in separate boxes, followed by the first transistor hearing aid in 1953. The birth of first implanted pacemaker is dated in the years 1957/58, developed by R. Elmqvist and A. Senning in Sweden⁸, and in parallel by E. Bakken and W. Lillehei in the US⁹.

2. Characteristics

In the popular press, the notion of wearable computers has frequently been associated with people equipped

¹ <http://www.nsf.gov/>

² <http://www.cordis.lu>

³ http://www.cordis.lu/ist/directorate_c/health/projectbooklet/projects.html

⁴ Defense Advanced Research Projects Agency (DARPA), the central research and development organization for the US Department of Defense www.darpa.mil

⁵ <http://www.iee.org/publish/inspec/>

⁶ <http://www.wearable.ethz.ch/links-institutions.0.html>

⁷ <http://www.vdc-corp.com/>

⁸ <http://www.thebakken.org/artifacts/elmqvist.htm>

⁹ http://www.ieee.org/organizations/history_center/milestones_photos/pacemaker.html

with bulky head-mounted displays and heavy boxes on their belt. Our idea and vision of wearable computing as a personal assistant are less spectacular, but much better matched to the healthcare and wellness requirements.

Depending on the understanding and on the application area, the research community has defined wearable computers in several ways, either by their attributes, by their components or by their application. Wearable computers should be continuously available, seamlessly embedded in our daily outfit, enabling extended perception, providing context-aware functionality as well as proactive support in information processing, permanently useful and usable in a wide range of mobile settings [10,11]. S. Mann has extended this list [12] by the attributes ‘not monopolizing the user attention, useful as a communication tool, observable and controllable by the user’.

Our vision of the wearable Personal Health Assistant PHA combines these wearable computing features with the capability to monitor and determine the health status of the wearer continuously. Fig. 1 depicts a potential implementation of a PHA. Several sensors, distributed in clothes, transmit the measured physiological and context data over a body area network (BAN) to a computing unit (e.g. a PDA), which fuses the sensor data out of them, estimates the health status and communicates with the surrounding networks.

3. Architecture and Components

The diversity of application fields for wearable computers corresponds to today’s various systems architectures and components, from wristwatch computers [13] to robust survival smart clothing for arctic environments [14]. Our daily clothing – optimized over several centuries – shows a hierarchical structure. The underwear physically contacts our skin and has to fulfill high requirements concerning hygiene

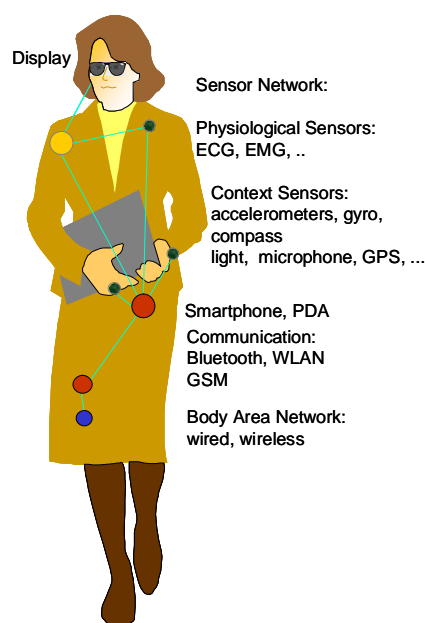


Fig. 1. Structure of a ‘Personal Health Assistant’ PHA.

and comfort. The outer clothing levels are exposed to the environment. We select them according to our personal preferences and business, mostly divided into garments we wear permanently, and garments like a coat we change several times during the day. Our group has proposed the System-on-Textile (SoT) integration concept for wearable computers, which con-

siders the structure and functionality of our clothes [15]. The wearable computer is partitioned into four functional levels, functional textiles, embedded microsystems, attachable peripherals and standard mobile components as depicted in Fig. 2.

1. Functional Textiles

Besides food and shelter, clothing is a basic need for human kind. About six thousand years ago, man started to replace the inflexible and uncomfortable animal skin by manufactured textiles. The body protection function has been enlarged by aesthetic attributes. Beyond their protective and aesthetic functions, clothes as our second skin have the potential to acquire an additional functionality as a personalized and flexible information platform [16]. For wearable computing, textiles can provide information and power transmission capabilities, sensory functions and an infrastructure for embedded microsystems.

Conductive Textiles. Originally developed for antistatic behaviour, conductive textiles can act as an interconnection substrate for electronic systems substituting cables in clothes. We distinguish three types of conduc-

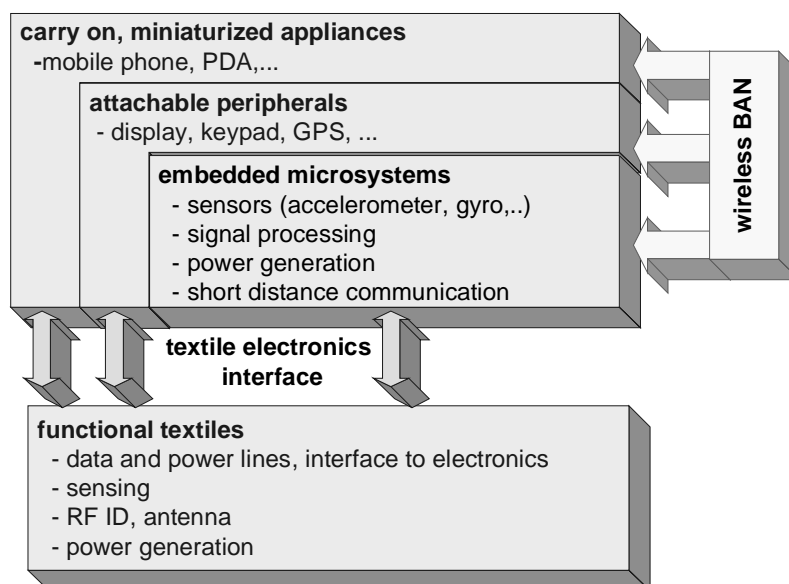


Fig. 2. The architectural level of a wearable system.

tive threads [17] which can be woven or knitted in standard manufacturing processes: (i) fibers filled with carbon or metal particles, (ii) fibers coated with conductive polymers or metal, (iii) thin metal or plastic conductive threads, spun with synthetic fibers. Fig. 3 shows an example of a woven conductive fabric [18] (type iii). Measurements confirm that these conductive textile are suitable for data transmission [18]: more than 100Mbit/s can be transmitted over a distance of 1 meter, therefore sufficient for a textile body area network (BAN). The performance remains unchanged even if the textiles are creased and stretched. Several groups have developed textile data networks using conductive threads, e.g. [19,20].

Antennas. Beside wired connection wireless communication channels are also necessary to enable the data exchange between the on-body components and to the user's environment. For the body-area network BAN several communication schemes are available. Magnetic induction with textile coils can effectively bridge distances less than 2 cm, e.g. between trousers and a shirt [18].

Fig. 4 shows an application of magnetic induction, the connection between the MP3-player box and the earphones in the shirt. Similar approaches have been proposed for textile transponder systems (RFID tags) [21]. Magnetic induction suffers from the low power efficiency at longer distances. Fig. 5 shows a novel textile antenna for Bluetooth applications, which can be sewn into garments. Three textile layers form this circularly polarized antenna [22].

Functional Threads: Smart textiles are characterized by their ability to sense, react and adapt to the environment. For wellness and healthcare applications, strain-sensitive fabrics enable the monitoring of body motion and change of shape [23,24]. For example, in [25] an undershirt for con-

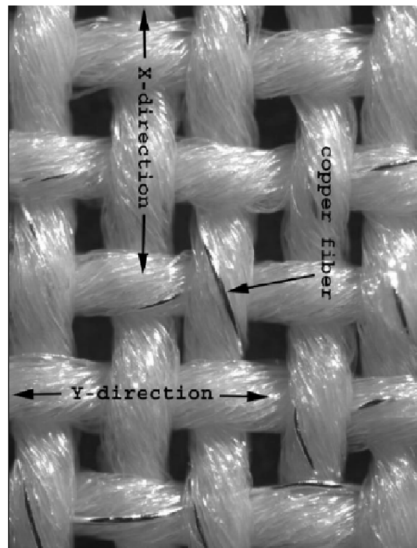


Fig. 3. Matrix woven fabric with metal fibers [18].

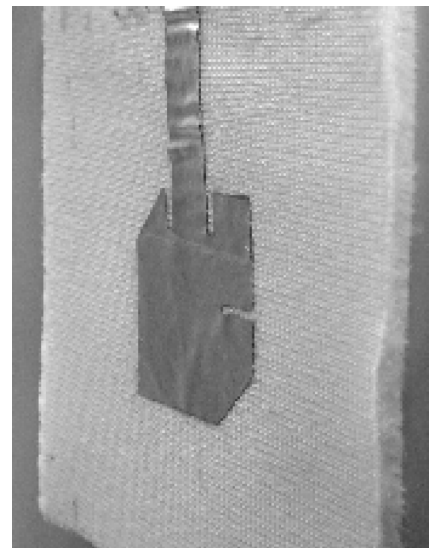


Fig. 5. Textile circularly polarized antenna with a single inset microstrip feed-line, designed for Bluetooth applications; width: 48 mm, length: 51 mm.



Fig. 4. Wireless connection between MP3-player and the on-shirt textile connection to the earphones using sewed textile coils.

tinuous cardiopulmonary recording has been proposed using woven or knitted strain-sensitive yarns. Textile pressure fabric (e.g. in [26]) integrated in underwear or in a wheelchair, can prevent decubitus by detecting when the user has been seated in a certain posi-

tion for too long. Textile touchpads as distributed tactile interfaces utilise multilayer configurations either with a pressure sensor [27] or a partially conductive layer [28]. The sensitive skin idea, proposed in [29], describes a large-area, flexible array of sensors

which could cover the surface of a machine or a part of the human body aiming at the sensing of the user's surroundings. Smart textiles can also take over actuator functions. Fibers coated of electro active polymers could behave similar to muscles, then often named as 'artificial muscles' [30]. For individuals with spinal cord injury, functional electrical stimulation (FES) enables restoration of movements [31]. Using conductive textiles, the electrodes for the stimulation can be integrated into the clothes of the patient.

2. Embedded Microsystems

As described below, the knowledge of the user's context is an essential feature in user-centered healthcare systems. The heterogeneity of possible contexts demands for the data fusion of various sensors. Vision and speech recognition are established tools to mirror the human's perception, but context detection using vision and speech creates a high computing load. The use of different, simple sensors can reduce the communication and computational effort [32]. To provide sufficient signal quality, most sensors need to be positioned at a particular body location, often in direct contact with the wearer's body or the environment. Because of the progress in microsystem technologies over the last decade, many sensors become small enough to be integrated in our daily outfit.

As in all mobile systems, generation and storage of electrical power remain a critical issue. Microgenerators can ensure the autonomous life of microsystems. T. Starner has summarized the harnessing of energy during the user's everyday actions, mainly through leg motions and body heat [33]. Three forms of energy harvesting are well matched to wearable computing: using solar cells, mechanical and thermal energy. To give an average figure, a 50cm² solar cell, mounted on the shoulder, generate between 0.15-

5mW indoors and 50-300mW outdoors, a 50cm² thermo-electric element achieves around 1.2mW, whereas a mechanical generator – weighing 2 grams and mounted at the knee - provides approx. 0.8mW [34].

Several technologies become available for the embedding of microsystems, either directly in fabrics, or in clothing components like buttons. As a design example [35], Fig. 6 shows an autonomous sensor button, consisting of a light sensor, a microphone, an accelerometer, a microprocessor and a RF transceiver. A solar cell powers the system even for continuous indoor operation.

3. Attachable Peripherals

Add-on modules, attached to our clothes and using the textile infrastructure customize the functionality of the wearable computer to user needs and user situations. IO interfaces e.g. keyboard, display and batteries determine the bulkiness of many appliances aggravated by the fact that each device uses its own keyboard, display and battery. Placing IO de-

vices and other peripherals in the user's outfit and allowing different appliances to share them through the textile infrastructure enable a more convenient interaction in a mobile user setting. Some examples should reflect the state-of-the-art in mobile IO interfaces. In display technologies, we identify two major developments as being attractive for wearable computing, microdisplays and flexible displays. Fig. 7 shows the view through a head-mounted microdisplay device, which is attached to normal glasses. The output of this see-through display overlays the user's real view allowing a mixture between the real and the virtual world. In retinal scanning displays, a laser beam is directly projected onto the human retina providing a widely accommodation-free focusing [36,37]. In the last years, several companies have intensified research in large-area flexible displays, either based on liquid crystal [38] or organic light emitting diode (OLED) technology. When attached to the sleeve, for example, the displays can be read off on a bended forearm.

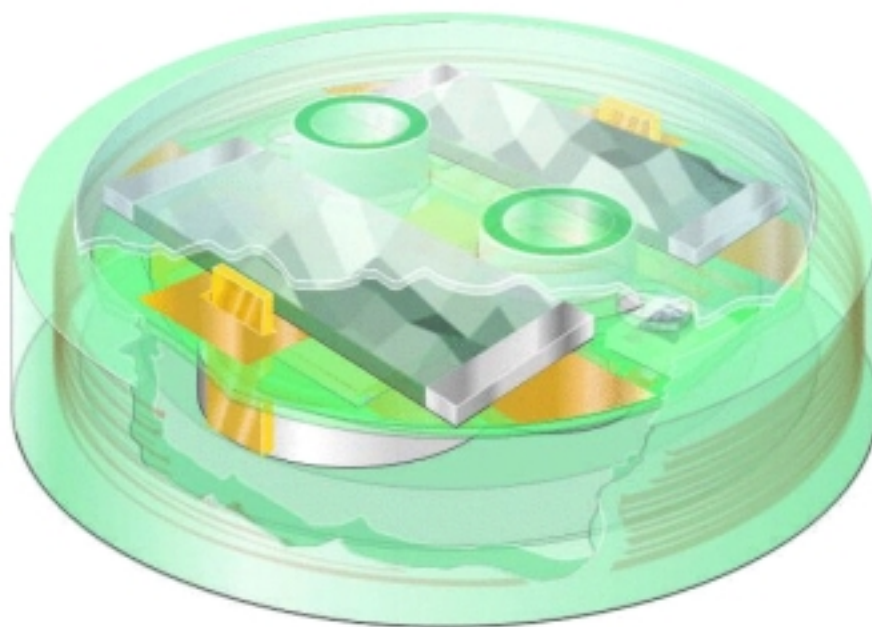


Fig. 6. Design of an autonomous 'sensor button', diameter 15mm, height 5mm [35].



Fig. 7. Microdisplay (Microoptical Corp, <http://www.microopticalcorp.com>) mounted on eyeglasses.



Fig. 8. Twiddler one-hand input devices.

Voice, motion and gestures are suited to controlling a computer without losing contact or attention to the environment. Miniaturized microphones fit into collars, as already presented in a snowboard jacket¹⁰. The so-called 'twiddler' mobile keyboard (Fig. 8) combines a mouse pointer and 18 keys, which can be operated with only one hand without direct visual contact¹¹. A glove equipped with strain



Fig. 9. ETH-QBIC – a mobile computer (Xscale CPU, 256 MB SRAM, USB, RS-232, VGA, Bluetooth) integrated in a belt buckle; the belt houses the flexible batteries and interface connectors [44].

sensors can track the movement of individual fingers and extract predefined gestures [39]. The 'FingerMouse' concept, presented in [40,41], sets glove aside but uses a miniaturized camera mounted on the user's chest to monitor hand gestures. First results have been presented to employ electromyogram (EMG) signals from the muscles to capture gestures and to take these as computer input commands [42,43].

4. Appliances

The fusion of the mobile phone, PDA (Personal Digital Assistant) and even MP3 player into 'smartphones' offers an interface between the personal communication environment and public services including the internet. Additionally the 'smartphone' can be connected to the components in the clothes using e.g. the Bluetooth communication system. But today's 'smartphones' require manual handling and focusing on the interface. Stripped of bulky IO interfaces and large batteries, mobile computing and communication modules are small enough to be easily carried in a purse or be part of carry-on accessories such as a key chain or a belt buckle as depicted in Fig. 9 [44].

The lower functional levels of a wearable system – functional textiles, embedded microsystems and peripherals – are located near to the human body, but they are dedicated to a single user: for example, underclothes with woven ECG-electrodes will be offered in different sizes. But the 'smartphone' like appliances belong to its user personally, he uses it daily also as storage of his private data.

4. Context Awareness

Often the attributes 'mobile', 'portable' or 'wearable' are used synonymously. We distinguish 'wearable systems' by their ability to automatically recognize the activity and the behavioral status of a user as well as of the situation around him, and to use this information to adjust the systems' configuration and the functionality [45]. This concept of context awareness constitutes the crucial feature of personal healthcare systems: only fusing the status of the user with the surroundings allows a reasonable comprehension of the vital parameters.

¹⁰ <http://www.wearable-electronics.de>

¹¹ <http://www.handykey.com/site/twiddler2.html>

Several attributes define context awareness, e.g. the user context, the environmental context and the social context. The user context comprises e.g. the user's motion and activity, gestures, biometric data and health status also including the affective and emotional state like stress and depression. The location, both indoor and outdoor, the time, the weather, the illumination and noise characterize the environmental context. The social context includes the people in the surroundings, the contact to and the communication with them.

As described below, context recognition relies on the sensor data. In [32] recommendations are presented which sensors or which combination of sensors are appropriate to detect specific context components. Several

methods and tools have been proved for data fusion, feature extraction and classification as depicted in Fig. 10. The Bayesian decision theory offers a fundamental approach for pattern classification (explained e.g. in [46]). Nonparametric techniques like the k-nearest neighbor approach enable the design of decision functions only based on sample patterns. The Kalman filter or the recently proposed particle filter approach [47] are helpful tools for the tracking and monitoring of states, for example, of hand gestures in video sequences. Hidden Markov Models and the Viterbi algorithm are appropriate to estimate a sequence of decisions. The adaptive and learning properties qualify multilayer neural networks for context recognition by the training with re-

petitive presentations of the target values, e.g. motion patterns.

In the past years, notable results in on-line context recognition have been achieved: scenarios in defined setups can be detected with sufficient accuracy. But these systems are by far not capable of interpreting arbitrary real-world situations. Progress in multimodal data processing, in cognitive science and artificial intelligence could pave the way for wearable systems, which understand most real-life scenes.

5. Ubiquitous Computing and Ambient Intelligence

Driven by the miniaturization of electronic systems and by the availability of wireless communication, M. Weisers's visionary view 1991 [48] of a disappearing computing world is now

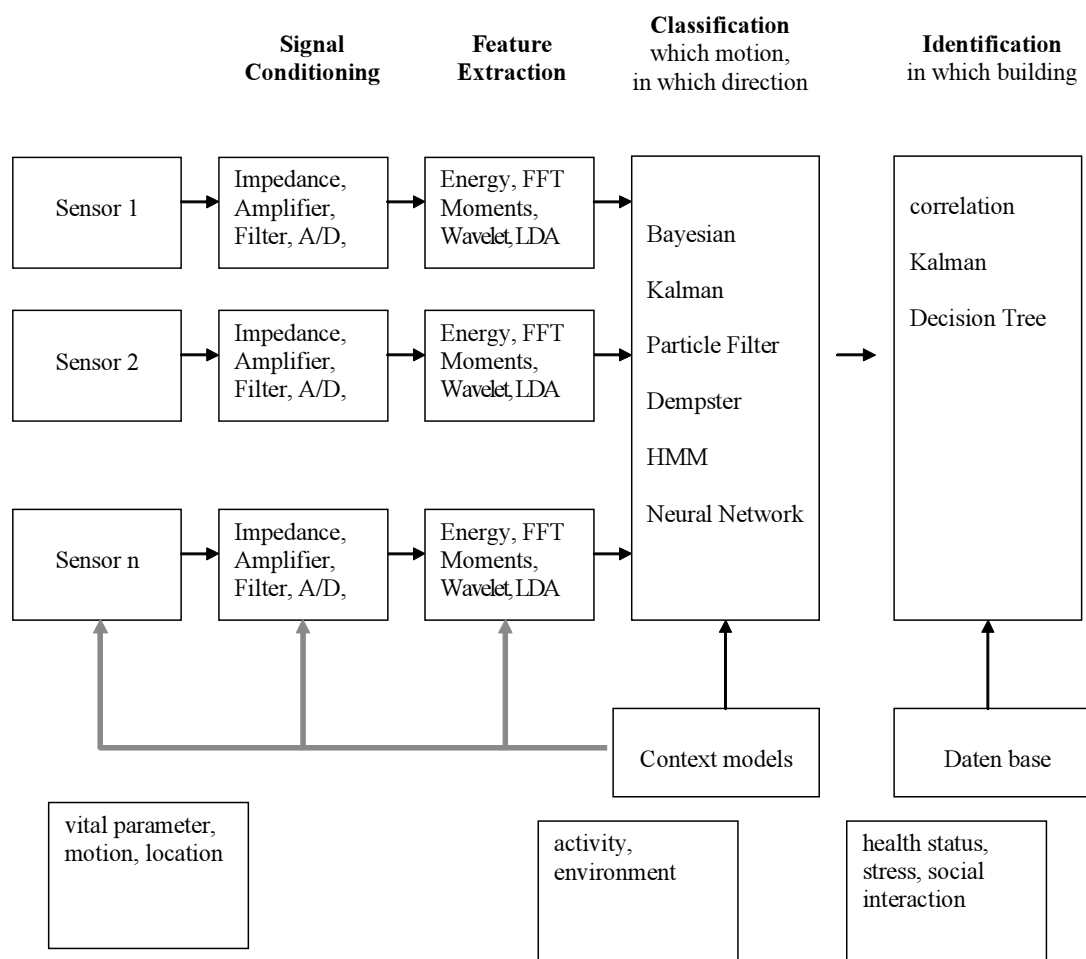


Fig. 10. Context recognition data path.

coming to fruition. Hundreds of tiny autonomous systems, consisting of sensors, signal processing and transmitter units, maybe in the size of a grain of rice, are distributed in the environment; they can observe the environment and communicate the data through ad-hoc organized wireless networks. RFID tags are the fore-runner: attached on each artifact around us, these electronic markers allow the detection of their location and they also provide information about the attached artifact. The technological as well as the social consequences of this ambient intelligence are far reaching as described in [49]. The impact of a computerized environment on personal healthcare varies from monitoring of people with cardiac risks [50] to home care for the elderly living alone [51].

3. Mobile Sensing of Vital Parameters

Several vital parameters and the their fusion define the individual health status in the Personal Health Assistant PHA. Data fusion, feature extraction and classification are established methods in pattern recognition. Fig. 10 shows the data path in a wearable health monitoring system. Sensors as part of our daily outfit observe the wearer and the environment. A variety of signal processing procedures enable the extraction of features like heart and respiration rate using the cleaned sensor data. Higher-level context requires the fusion of several features and sensor data; for example, the pooling of vital parameters with activity and behaviour

patterns permits the rating of cardiovascular risk factors like stress.

This chapter deals with wearable biosensors for the detection of specific features like heart rate, whereas the next chapter focuses on classification and identification of higher-level context. Following the focus of this paper on non-invasive diagnostics, we concentrate on sensors, which acquire signals from surface electrodes [52].

1. Motion

Tracking of body motions, gestures and positions provide information useful for activity classification, for denoising of other biosignals, e.g. ECG, and for interpretation of the physiological status. Accelerometers, gyroscope, magnetometer, piezoelectric sensor and GPS (global positioning system) are often combined to detect motion.

Miniaturized accelerometers are fabricated using MEMS (Micro-Electro-Mechanical Systems) technologies by several manufacturers¹² in high volume mainly as airbag sensor in cars. The maximum measurements range spans from 4g to 100g, with a resolution of 8 to 10 Bit and a maximal data bandwidth between 200Hz and 6kHz, in 1, 2 or 3 accelerometer detection axes; prices are between 5\$ and 15\$.

MEMS-based gyroscopes became available in the last years. The 1-axis ADXRS3000 device¹³ measures 7x7x3mm; it consumes about 6mA at 5 V, the price is about 30\$. Monolithic magnetic compasses show a similar size, e.g. the 2 or 3 axes devices¹⁴ are packaged in 7x7x1,4mm.

The 'Actigraph' wrist-worn motion logger¹⁵ uses miniaturized accelerometers to monitor and record activity

and sleep pattern over 24 hours. PC tools allow the analysis of the downloaded data. Also a list of applications¹⁵ is given, ranging from the detection of sleep-wake rhythm, hyperactivity disorder to locomotor activity rhythms in Alzheimer's disease.

Piezoelectric material generates an electric voltage if physically distorted. This effect qualifies it for limbs movement sensing [24].

Using at least four orbiting satellites, the Global Positioning System (GPS) sensor determines the position (and therewith also speed and acceleration), but is restricted to outdoor environment.

2. Heart Rate Monitor and ECG

Heart rate, itself as well as the heart rate variability are cornerstone in determining human physiological status. Heart rate variability (HRV) has gained increasing interest as an indicator for the cardiovascular autonomous nerve system.

In 1893, W. Einthoven introduced the term 'electrocardiogram' (ECG), an invention, for which he was awarded the Nobel Prize in 1924. One of the first – more or less – mobile ECG knapsack weighed 37 kg, developed by J. Holter in 1949. Today the so-called Holter monitor allows a continuous ambulatory ECG up to 72 hours, housed in a matchbox sized case with three cables connected to the chest via electrodes. Several Holter monitoring devices are already available on the market¹⁶. The model MT-120¹⁷ includes a mobile phone module which transmits one hour of recorded data within 6 min e.g. to a medical care center.

¹² <http://www.silicondesigns.com/>, <http://www.st.com/stonline/products/selector/444.htm>
http://www.analog.com/IST/SelectionTable/?selection_table_id=110

¹³ <http://www.analog.com/en/prod/0,2877,764%255F801%255FADXR300,00.html>

¹⁴ <http://www.ssec.honeywell.com/magnetic/hmc6352.html>.

¹⁵ <http://www.ambulatory-monitoring.com/>

¹⁶ <http://www.cardguard.com>, <http://www.delmarmedical.com/products/digicorder.html>

¹⁷ <http://www.schiller.ch>

Considering the heart as an electrical generator, electrodes have to contact the skin directly to measure the electrical potentials. Silver-chloride electrodes are widely used; flexible conductive yarns made from metal glad aramid fibers, soft polymers or conductive rubber can be woven in textiles, or attached by an additional layer. The kind of measurement – e.g. the complete Q, R, S and T waves or only the R-to-R distance - determines number and position of the electrodes. A thoracic band can house electrodes on the chest and on the back, also for respiration and skin temperature. The placement of electrodes in the underpants [53] might be more convenient for the wearer; furthermore the higher contact reduces the contact resistance from the electrode to the skin. Instead of a fixed and personalized position of the electrodes, an array of electrodes could be distributed in the garment; those electrodes with the most reliable signal strength are selected continuously. Given the raw ECG data, several software tools have been developed to extract the characteristic points, e.g. the WFDB¹⁸ software from MIT, Boston.

Considering the heart as a moving muscle, which modulates an electromagnetic wave according to the Doppler effect, the measurement of the heart activity is possible without direct contact to the skin [54]. A single-chip implementation has already been presented in [55]. Although radar signals do not provide a similar information spectrum compared to the classical ECG analysis, they allow a distance measurement well suited for home monitoring.

Considering the heart as a pump, the changing blood volume can be mea-

sured by the electrical resistance at the body surface, known as impedance plethysmography or the impedance cardiography method (described e.g. in [56]). Normally, using two electrodes, at the neck and the abdomen, an injected AC current generates a voltage longitudinally over the thorax, which can be measured using two additional electrodes.

Considering the heart as a noisy pump, microphones mounted on chest-wall in the primordial region can also monitor heart rate [57]. On a simplified view, this phonocardiographic (PCG) sensor replaces the well-known mechanical stethoscope. In [58], a (PCG) sensor set on a water-mat or air-mat extracts the heart rate and respiration while sleeping.

3. Respiration

Several wearable sensors are available to measure the respiration rate as an important vital parameter. The respiration is associated with the kinematics of the chest and therewith with changes of the thoracic volume. The electric impedance plethysmography - also used in the ECG monitors (see above) - measures these changes. The respiratory inductive plethysmography (RIP) employs two conductive wires, one around the ribcage and the other around the abdomen. Motions of the chest wall cause changes of the self-inductance of the two loops (implemented e.g. in the XactTrace system¹⁹). Magnetometers or linear-displacement sensors can detect changes in the chest diameter and perimeter. For example, strain gauges wrapped around the torso are suited for the embedding into clothes. Piezoresistive materials are mainly used as displacement sensor²⁰.

4. EMG

Electromyography (EMG) means the measurement and recording of the functioning skeletal muscle. Needles or surface electrodes, applied preferably at the belly of the muscle, detect the stimulation signals of the muscle fibers. The low voltage amplitude in the range of 1.5mV (rms), the crosstalk from other adjacent muscles and artifacts caused by motions require a sensitive signal processing approach. Electromyography visualizes the timing of muscle activation and magnitude of the force produced by the monitored muscle [59]. Additionally, advanced signal processing techniques can identify muscle fatigue during dynamic contractions. There are several commercial EMG devices on the market, e.g. from Motion Lab²¹. A survey of systems and evaluation software has been given in [59].

5. Blood Pressure

Although blood pressure has been an important physiologic parameter, no fully satisfactory ambulant sensor exists up to now. The traditional method relies on a pump in a cuff enabling the detection of the systolic and diastolic arterial blood pressure. Ambulant twenty-four hours blood pressure measurement setups are available using a small cuff and a controlling box (e.g. Schiller BR-102¹⁷). In wrist blood pressure monitors, the pump and the evaluation electronics are integrated in an 'oversized' watch-type box (e.g. OMRON HM-630²²). Although small, these devices are not fully wearable and unobtrusive, therefore various approaches have been undertaken to design cuff less blood pressure monitors, mostly using multi-modality data. In [60], a noninvasive photo plethys-

¹⁸ <http://ecg.mit.edu>

¹⁹ <http://www.medicare.com/products/studyaccess/xact/index.asp>.

²⁰ <http://www.adinstruments.com/products/product.php?id=MLT1132>

²¹ <http://www.emgsrus.com/>

²² <http://www.omronhealthcare.com/>

mograph (PPG) sensor has been proposed which is calibrated using a known patient-controlled hydrostatic perturbation value. The approach in [61] also uses PPG values and combines them with ECG and pulse-transit-times; after the calibration with conventional blood pressure meters, two signals from the user's finger are sufficient to estimate the systolic and diastolic pressure with a mean error of 1.82mmHg and of 0.45mmHg, respectively.

6. Blood Oximetry

Non-invasive transducers applied directly to the skin can measure the partial pressure of oxygen (PO₂) indicating the alveolar ventilation, and the oxy-hemoglobin saturation (SpO₂), determining the amount of oxygen in blood. The absorption of infrared light depends on SpO₂ enabling the saturation pulsed oximetry measurement method using infrared emitting diodes (LED) and receiver photo-detector diodes. The reflectance principle assumes the emitter and receiver diodes side by side of the tissue, for example on the wrist, whereas the transmittance method places them on each side of the tissue, e.g. on the fingertip. The oximetry shows a significant sensitivity on body movement, condition of the tissue and sensor displacement. Mobile devices become available which include various artifact-removing techniques²³. In [62], a reflectance prototype oximetry measurement system including a RF data transmission unit has been miniaturized in a finger-ring configuration.

7. Skin

As our biggest organ, the skin enables the noninvasive access to sev-

eral body related parameters, the temperature, the perspiration and the electrical impedance. Thanks to temperature sensitive materials, small electrodes in direct contact with the skin can measure the skin temperature with an accuracy below 0.1°C°, demonstrated by several commercially available devices; e.g. the low-power silicon temperature in [63] with a size of 3x3x1.5mm, or the negative varying resistor in [64] with a size of 2x1.25x0.5mm.

The electrical surface skin resistance varies between 1MΩ and approx. 100kΩ mainly due to perspiration. A DC or AC current injected at two electrodes e.g. on the palm of the hand, generates a voltage-drop that can be measured. Because of the relation between perspiration, autonomous nervous system and the physiological status, the skin resistance can be an indicator for stress, anxiety, fear and conflict as already investigated e.g. in [65]. Combining this Galvanic Skin response (GSR) with other vital parameters like heart rate and body temperature, the emotional state of patients can be estimated [66]. The approach of a sensitive or electronic skin [67] envisions a system, which can sense its surroundings using touch, pressure, temperature and other sensors. This electronic skin would enable machines to become cautious and would increase the sensing abilities of human prosthetics.

8. Wearable Health Systems

The health and wellness market already offers a broad spectrum of wearable devices, which deduce the wearer's health status based on the

continuous measurement of several vital parameters. Some examples should illustrate the status. The flexible belt of Polar²⁴ accommodates a one-channel ECG and a transmitter to send the data to the wrist receiver. The analysis of the heart rate enables the management of fitness, weight, rehabilitation as well as professional training. The Bodymedia HealthWear Armband²⁵ is worn on the back of the upper right arm; focusing on weight management, it measures movement, heat flux, skin temperature, near-body temperature, and galvanic skin response, allowing accurate calculations of energy expenditure. VivoMetrics²⁶ developed a 'LifeShirt System' affording the continuous ambulatory monitoring system of pulmonary, cardiac and other physiologic data, dedicated mainly for research. ECG, accelerometers and sensors for respiratory measurement are embedded in undershirt garment; an external PDA stores the data and extracts the vital parameters. The Stanford Lifeguard system²⁷ has been designed for extreme environments. It comprises physiological sensors (ECG/respiration electrode patch, pulse oximeter, blood pressure monitor), a wearable cigarette packet sized box, and a base station.

4. Wearable Technology's Applications

Single vital parameters like ECG do not normally allow rating the individual health status or the life style as risky or harmless concerning health. Also nutrition, activity, the balance between

²³ <http://www.novamatrix.com/products/2001/2001.htm>,
http://www.anestech.org/Publications/Annual_2000/Jopling2.html,
http://www.dolphinmedical.com/faqs/Voyager_210_UCSF_Abstract.pdf

²⁴ <http://www.polar.fi/>.

²⁵ <http://www.bodymedia.com>.

²⁶ <http://www.vivometrics.com/>

²⁷ <http://lifeguard.stanford.edu/>

stress and relaxation, the sleep quality and finally the social settings determine the individual health status and wellbeing. Over the last years, several research activities following an integral approach in human physiology and focusing on the continuous detection of the health status have shown an increasing interest in wearable systems because of the permanently available platform close to the human body. In the next sections, some results are given also reflecting the state-of-the-art in detection of complex situations.

1. Activity

Motion, motion pattern, gestures and postures are basic elements characterizing human activity. As described above, accelerometer, gyroscope and compass sensors are available in miniaturized and wearable forms, being precise enough to enable the detection of complex motion patterns. As proved in [68], body-mounted inertial sensors can acquire the kinematics of gait with a precision comparable to the VICON 3D²⁸ optical-based, stationary motion capture system. This wearable sensors platforms make the detection of physiologically relevant motion pattern possible. For example [69], an accelerometer system, fastened by an elastic waist belt to the subject's back in the lumbosacral region, enables the assessment of the motor recovery system and of the effectiveness of physical therapy of poststroke hemiplegic (PSH) patients. In [70] a significant correlation between cadence and gait velocity of depressed patients, but not in healthy controls could be verified. The fusion of several sensor data streams can detect even complex gestures as used in the American Sign Language (ASL) for deaf people. In [71] it has been shown, that combining a vision system, mounted on the head, and accelerometers on the wrist

could be a promising approach for an automatic ASL recognition system.

2. Stress and Emotions

The notion 'Affective Computing' as introduced in [72] sketches machines which have the skills to recognize their user's affective expressions, and to respond intelligently. These affective expression also includes stress, emotions and other psychological symptoms. Wearable systems afford the noninvasive sensing of physiological pattern. In [73] e.g., four wearable sensors (EMG, SpO₂, skin conductance, respiration sensor) have been applied to detect and to classify eight different motions like anger, grief, joy or hate with a classification accuracy between 60 and 70 percent. Acoustical properties of speech which can easily be recorded by a collar microphone, are suited as indicators of depression and suicidal risk, as described in [74]. To measure and to evaluate face-to-face interaction between people within a community, a wearable 'sociometer' has been built [75], consisting of an IR transceiver and a microphone. A computational framework extracts socially relevant aspects e.g. identifying dynamics and style of person's interactions from the raw sensor data. Two recently started EU-projects within the 6th Framework Programme are related to behavioral medicine. The INTREPID³ project aims at developing a multi-sensor context-aware wearable system for the treatment of phobias. Also project AUBADE³ will design a wearable platform for analyzing the emotional states in real time, using signals obtained from the face.

3. Rehabilitation and Aging

At least three percent of the population over the age of 65 is affected

by Parkinson's disease (PD). Classifying of motion pattern using wearable technology would create new clinical applications in the treatment of PD. For example, accelerometers attached on the wrist, provide data of PD patients to detect tremor (with a specificity of 95 percent) and dyskinesia (with a correct classification also of 95 percent) in daily life [76]. About 15 percent of all strokes are caused by atrial fibrillation. Research, for example in the EU-Project MyHeart [77] focuses on the design of a PHA being able for an early and mobile detection of atrial fibrillation, allowing immediate treatments e.g. by medication. Post-stroke neurological recovery can be stimulated by exercise and perhaps by medications [78]. Wearable sensors within the PHA are necessary to capture the motor activity and to assess the effects and efficacy of treatment interventions.

Wearable PHAs will open a new horizon not only for PD and stroke treatment, they will also play a key role in telerehabilitation, standing for a remote monitoring and therapy of patients at home. As summarized in [79], the still existing 'knowledge gaps' in applying of telerehabilitation are localized mainly on the user-centered management of information, less on wearable devices and wireless telecommunications.

Aging-in-place is closely related to rehabilitation and home-based health-care but additionally it has to consider the conditions and needs of elderly people. The spectrum of tools spans from fall detectors (e.g. in [80]) to completely 'smart homes' as alternatives to ensure the independent life of elderly and disabled people [81]. Intelligent devices, embedded in the home environment and collaborating with the mobile and wearable intelli-

²⁸ <http://www.vicon.com/>

gence like the PHA provide the infrastructure for an emotionally human-friendly, convenient as well as reliable 24-h health monitoring. Several programs deal with that field, lists are given e.g. in [4,81].

Outlook

The sketched wearable 'Personal Health Assistant' PHA as a minimally obtrusive platform for individualized health service will be the key enabler technology pushing the paradigm shift from the established centralized medical care to a user centred overall lifestyle health management. The proposed 'Life Balance Factor' LBF compiles the current physiological state and translates it into a layperson's language.

What could be the main road blocks and problems to be solved on that way? Smart clothes pose two critical challenges: On the one hand, the acceptance of the potential users to put the smart clothes on daily demand for a high level of wearing comfort and intuitive handling. On the other hand, cooperations between clothing manufacturers, electronic suppliers and the retail have to be established to close the manufacturing, trading and maintenance chain. Furthermore, the PHA as a mobile and communicating device has to be embedded in the local and national IT landscape, involving net provider, private and public health services. Finally, maybe the most critical problem because of the necessary interplay of many partners with partly conflicting interests: the PHA has also to be integrated in the well-established health organizations, including the family doctor, caregivers, first aid organizations, drug makers, pharmacies, hospitals, and completing, the health insurances. Considering all these manifold challenges, the ongoing projects in academia and indus-

try indicate that we will see first commercially available PHAs in two to three years from now.

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