A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis

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***Abstract*—The design and development of wearable biosensor systems for health monitoring has garnered lots of attention in the scientific community and the industry during the last years. Mainly motivated by increasing healthcare costs and propelled by recent technological advances in miniature biosensing devices, smart textiles, microelectronics, and wireless communications, the continuous advance of wearable sensor-based systems will potentially transform the future of healthcare by enabling proactive personal health management and ubiquitous monitoring of a patient's health condition. These systems can comprise various types of small physiological sensors, transmission modules and processing capabilities, and can thus facilitate low-cost wearable unobtrusive solutions for continuous all-day and any-place health, mental and activity status monitoring. This paper attempts to comprehensively review the current research and development on wearable biosensor systems for health monitoring. A variety of system implementations are compared in an approach to identify the technological shortcomings of the current state-of-the-art in wearable biosensor solutions. An emphasis is given to multiparameter physiological sensing system designs, providing reliable vital signs measurements and incorporating real-time decision support for early detection of symptoms or context awareness. In order to evaluate the maturity level of the top current achievements in wearable health-monitoring systems, a set of significant features, that best describe the functionality and the characteristics of the systems, has been selected to derive a thorough study. The aim of this survey is not to criticize, but to serve as a reference for researchers and developers in this scientific area and to provide direction for future research improvements.**

***Index Terms*—Biosensor, body area networks, health-monitoring, wearable systems.**

I. Introduction

Wearable health-monitoring systems (WHMS) have drawn a lot of attention from the research community and the industry during the last decade as it is pointed out by the numerous and yearly increasing corresponding research and development efforts [1]–[3]. As healthcare costs are increasing and the world population is ageing [4], there has been a need to monitor a patient's health status while he is out of the hospital in his personal environment. To address this demand, a variety of system prototypes and commercial products have been produced in the course of recent years, which aim at providing real-time feedback information about one's health condition, either to the user himself or to a medical center or straight to a supervising professional physician, while being able to alert the individual in case of possible imminent health threatening conditions. In addition to that, WHMS constitute a new means to address the issues of managing and monitoring chronic diseases, elderly people, postoperative rehabilitation patients, and persons with special abilities [5], [6].

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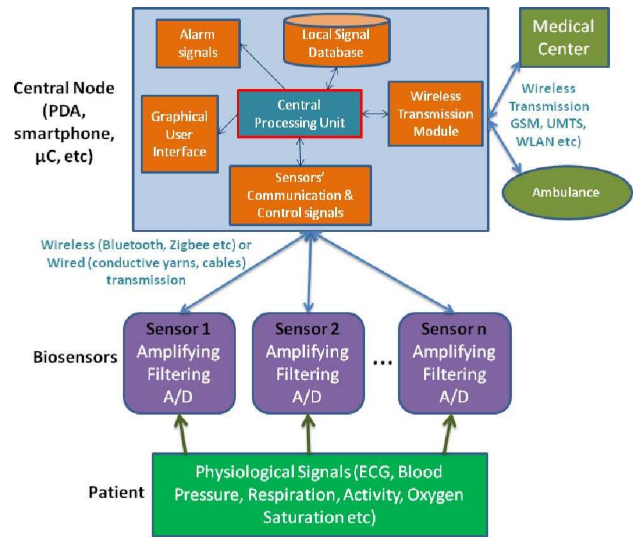

Fig. 1. Architecture of a wearable health-monitoring system.

Wearable systems for health monitoring may comprise various types of miniature sensors, wearable or even implantable. These biosensors are capable of measuring significant physiological parameters like heart rate, blood pressure, body and skin temperature, oxygen saturation, respiration rate, electrocardiogram, etc. The obtained measurements are communicated either via a wireless or a wired link to a central node, for example, a Personal Digital Assistant (PDA) or a microcontroller board, which may then in turn display the according information on a user interface or transmit the aggregated vital signs to a medical center. The previous illustrates the fact that a wearable medical system may encompass a wide variety of components: sensors, wearable materials, smart textiles, actuators, power supplies, wireless communication modules and links, control and processing units, interface for the user, software, and advanced algorithms for data extracting and decision making.

In Fig. 1, a general WHMS architecture is depicted, in accordance to the described system's functionality and components. However, this should not be perceived as the standard system design, as many systems may adopt significantly varying architectural approaches (for example biosignals may be transmitted in analog form and without preprocessing to the central node

TABLE I
BIOSENSORS AND BIOSIGNALS

Type of Bio-signal	Type of Sensor	Description of measured data
Electrocardiogram (ECG)	Skin/Chest electrodes	Electrical activity of the heart (continuous waveform showing the contraction and relaxation phases of the cardiac cycles)
Blood pressure (systolic & diastolic)	Arm cuff-based monitor	Refers to the force exerted by circulating blood on the walls of blood vessels, especially the arteries
Body and/or skin temperature	Temperature probe or skin patch	A measure of the body's ability to generate and get rid of heat
Respiration rate	Piezoelectric/piezoresistive sensor	Number of movements indicative of inspiration and expiration per unit time (breathing rate)
Oxygen saturation	Pulse Oximeter	Indicates the oxygenation or the amount of oxygen that is being "carried" in a patient's blood
Heart rate	Pulse Oximeter/skin electrodes	Frequency of the cardiac cycle
Perspiration (sweating) or skin conductivity	Galvanic Skin Response	Electrical conductance of the skin is associated with the activity of the sweat glands
Heart sounds	Phonocardiograph	A record of heart sounds, produced by a properly placed on the chest microphone (stethoscope)
Blood glucose	Strip-base glucose meters	Measurement of the amount of glucose (main type/source of sugar/energy) in blood
Electromyogram (EMG)	Skin electrodes	Electrical activity of the skeletal muscles (characterizes the neuromuscular system)
Electroencephalogram (EEG)	Scalp-placed electrodes	Measurement of electrical spontaneous brain activity and other brain potentials
Body Movements	Accelerometer	Measurement of acceleration forces in the 3D space

and bi-directional communication between sensors and central node may not exist).

As it is made obvious from the previous discussion, wearable systems for health monitoring need to satisfy certain strict medical criteria while operating under several ergonomic constraints and significant hardware resource limitations [7], [8]. More specifically, a wearable health-monitoring system design needs to take into account several wearability criteria, for instance, the weight and the size factor of the system need to be kept small and the system should not hinder any of the user's movements or actions. Furthermore, radiation concerns and possible aesthetic issues need to be accounted for. In addition to that, the security and the privacy of the collected personal medical data must be guaranteed by the system, while power consumption needs to be minimized to increase the system's operational lifetime. Finally, such systems need to be affordable to ensure wide public access to low-cost ubiquitous health-monitoring services.

The previous mentioned parameters of a wearable health monitoring system highlight the fact that designing such a system is a very challenging task since a lot of highly constraining and often conflicting requirements have to be considered from the designers. Furthermore, it is understandable that there is no single ideal design for such systems, but rather the tradeoff between "antagonizing" parameters should be balanced based on the specific area of application.

In this paper, the current state in research and development of wearable low-cost unobtrusive systems for health-monitoring is reviewed by summarizing and comparing the attributes of the most promising current achievements of several worldwide projects and commercial products. Section II presents the most important and widely employed biosensor technologies along with the corresponding measured biosignals. In Section III, short-range wireless communication standards for WHMS are discussed. Section IV reviews research and development on WHMS, while Section V presents the maturity evaluation of the reviewed systems according to the selected features. Section VI provides a discussion on the current shortcomings in system design, integration, and functionality based on the evaluation results. Furthermore, other challenging issues that have to be overcome in order for wearable biosensor systems to become more efficient and applicable as real-life solutions are also mentioned. Finally, Section VII concludes the paper.

II. Physiological Signals and Biosensors

This section provides a list of several sensing technologies as depicted in Table I, which can be integrated as part of a wearable health-monitoring system, along with their corresponding measured physiological signals. The measurement of these vital biosignals and their subsequent processing for feature extraction, leads to a collection of real-time gathered physiological parameters, which can give an overall estimation of the user's health condition at any given time.

III. Wireless Communication Standards for WHMS

As Fig. 1 illustrates, transmission of measured data in the overall context of WHMS needs to be performed for two different purposes: 1) for communicating the collected physiological signals from the biosensors to the system's central node; and 2) for sending the aggregated measurements from the wearable system to a remote medical station or to a physician's cell phone.

As mentioned in Section I, type 1) transmission of data or else short-range transmission can be handled either by wires or by multiple wireless links. In the former case, the user's mobility and comfortableness can be severely hindered by the use of wires and moreover there is an increased risk of system failure [9]. A more favorable approach to this matter is the use conductive yarns to transmit the measurements collected from sensors integrated on some type of flexible smart-textile clothing [10]. Alternatively, in the latter case, autonomous sensor nodes can form a body area network (BAN) or body sensor network

(BSN), usually in the basic configuration of a star topology, transmitting the data to the central node of BAN central node, which can be a PDA, a smart-phone, a pocket PC or a custom designed microcontroller-based device.

Regarding type 2) data transmission or else long-range communication between the WHMS and a remote station or device, there is a wide variety of available wireless technologies that can serve that goal. Such technologies include WLAN, GSM, GPRS, UMTS, and WiMAX, which can offer wide coverage and ubiquitous network access. Furthermore, future advances in 4G (fourth generation) mobile communication systems are expected to guarantee worldwide seamless access to the Internet at much higher data rates [11], and thus to facilitate more efficiently the need for gathering real-time measurements from a wearable health-monitoring system at a remote location. In this section, we will briefly discuss the features of the short-range wireless communication technologies that have been utilized so far for intra-BAN communication and comment on their applicability to WHMS.

The most commonly employed wireless communication standards in BANs are IEEE 802.15.1 (Bluetooth) and 802.15.4 (widely referred to as Zigbee, although Zigbee includes the specification of network, security, and application layers on top of the official standard), originally part of the 802.15 Working Group for wireless personal area network (WPAN).

The Zigbee standard [12] targets low-cost, low data-rate solutions with multimonth-to-multiyear battery life, and very low complexity. It operates in 16 channels in the 2.4 GHz industrial, scientific, and medical (ISM) band (250 kb/s, OQPSK modulation), in 10 channels in the 915 MHz band (40 kbps, BPSK modulation) and in one channel in the 868 MHz band (20 kb/s, BPSK modulation). It utilizes carrier sense multiple access—collision detection (CSMA-CA) channel access or synchronized channel access based on a beaconing mechanism and direct sequence spread spectrum (DSSS) coding. Maximum transmission range is about 75 m and supported network architectures include star, tree cluster, and mesh topologies. Finally, Zigbee uses an advanced encryption standard (AES) algorithm with 128-bit keys to guarantee message integrity and privacy and to perform authentication.

Bluetooth [3] is an industry specification for short-range RF-based connectivity between portable and also fixed devices. It is a low-power and low-cost RF standard, operating in the unlicensed 2.4 GHz spectrum. It uses a frequency hopping technique (FHSS) over 79 channels in the ISM band to combat interference and fading and it may support up to 3 Mb/s in the enhanced data rate mode and maximum transmission distance of 100 m (although 10 m is the most common mode). Its basic configuration is the piconet, a star topology network with one master and seven slaves, whereby the master provides the synchronization reference (common clock and frequency hopping pattern). Encryption is optional and is provided by a 64 or 128-bit SAFER+ algorithm, however, the Bluetooth framework is often found to be vulnerable to possible attacks and risks [14], [15]. Finally, the Bluetooth SIG announced recently the addition of two alternative protocol stacks, e.g., the Bluetooth low energy, an ultralow power technology for devices with limited battery

TABLE II
WIRELESS COMMUNICATION STANDARDS

	Range (typical)	Data Rate (max)	Power Cons.*	Cost per chip	Frequency
Zigbee	10-75m	20kbps/ 40kbps/ 250kbps	30mW	$2	868MHz/ 915MHz/ 2.4GHz
Bluetooth	10-100m	1-3Mbps	2.5-100mW	$3	2.4GHz
IrDA	1m	16Mbps	-	$2	Infrared
MICS	2m	500kbps	25μW	-	402-405 MHz
802.11g	200m	54Mbps	1W	$9	2.4GHz

*Power consumption refers to maximum consumed power when the chip is on and it is sending/receiving.

capacity and the Bluetooth 3.0 specification which adopts the Wi-Fi PHY/MAC layers for higher data throughput. The Bluetooth low-energy technology allows for consumption of only a small fraction of the power of the original Bluetooth products and amongst others is targeting sports and wellness, and healthcare devices.

Alternative technologies for short-range intra-BAN communication include infrared (IrDA), the medical implant communication service (MICS) and ultra wideband (UWB). IrDA is a low-cost communication protocol for short-range exchange of data over infrared light. Despite the fact that it is a low-power technology that supports up to 16 Mb/s speeds, it has the main disadvantage of requiring line-of-sight communication, thus making it impractical for WHMS applications.

MICS is an ultralow power, unlicensed, mobile radio service for transmitting low-rate data in support of diagnostic or therapeutic functions associated with medical devices [16]. It uses the 402–405 MHz frequency band, with 300 kHz channels. Effective isotropic rediated power (EIRP) is limited to 25 μW and targets mostly devices such as pacemakers and defibrillators. Despite its favorable characteristics, MICS has not been utilized widely by researchers due to the lack of commercially available MICS solutions. Finally UWB, operating in the frequency range of 3.1–10.6 GHz, is a standard that is inappropriate for BANs due to its high complexity and the unsuitable wide bandwidth modulation [4].

Table II provides a reference to the most important features of the most prevailing wireless technologies for WHMS from the ones discussed here. From the previous discussion, it has been made obvious that existing standards fail to address the requirements of BANs, either due to interference problems [17] or security concerns or form factor of hardware modules or power consumption. As a response to these issues, the 802.15.6 IEEE Task Group [18] is planning the development of a communication standard optimized for low power devices and operation on, in or around the human body. According to the TG6 reports, the standard under development should support scalable bit rates (from 1 kb/s to hundreds of Mb/s), it should be a short-distance protocol (2 m to maximum 5 m), it will allow network sizes of up to 100 devices, and it should guarantee very low latency and ultralow power consumption, e.g., 0.1–1 mW. Finally, the 2360–2400 MHz band has been proposed for medical BAN services, to leverage off-the-shelf component integration and to avoid interference from other wireless technologies.

IV. Research and Development in WHMS

In this section, several types of wearable health-monitoring systems are discussed. Since during the last 10 years there have been numerous research efforts and products that can be classified as WHMS, in this review, we attempt to categorize them: 1) based on whether they are commercial products or research prototypes; and 2) based on their hardware configuration, e.g., BAN-based, smart textile-based, microcontroller, or custom hardware-based, etc. Research efforts will be examined first, followed by a review on commercially available systems.

A. Research Prototypes

1) Systems-Based on a Microcontroller Board or on Custom Designed Platforms: Wearable systems that fall in this category are those that use some type of microcontroller board as a physiological data-collecting platform and that are usually based on wired transmission of biosignals from the sensors to the processing board.

The Media Laboratory of MIT, Cambridge, developed LiveNet, a flexible distributed mobile platform aiming at long-term health monitoring applications with real-time data processing and streaming and context classification [19]. LiveNet used a Linux-based PDA mobile device, a modular sensor hub (SAK2) for gathering, processing, and interpreting real-time contextual data and an integrated physiological board (BioSense), which incorporates a 3-D accelerometer, electrocardiogram (ECG), electromyogram (EMG), and galvanic skin conductance sensors, and which allows interfacing with a wide range of commercially available sensors. Furthermore a three-layer software architecture has been developed, which supports communication between group-based applications, efficient distribution and processing of higher bandwidth digital signals, and the implementation of real-time context classifiers for wearable applications. Finally, the MIT Wearable Computing Group, in collaboration with several healthcare providers, has initiated various pilot studies using the LiveNet system, which include soldiers' health monitoring in harsh environments, automated Parkinson symptom detection system, Epilepsy seizure detection and long-term behavioral modeling. Overall, LiveNet targets real-time feature extraction and classification of medical conditions, as well as closed-loop medical feedback systems.

AMON or the advanced care and alert portable telemedical monitor was a project financed by the EU FP5 IST program [20]. It resulted in the development of a wrist-worn device, which is capable of measuring blood pressure, skin temperature, blood oxygen saturation, and a one lead ECG. In addition to that it incorporated a two-axis accelerometer for correlating user activity with the measured vital signs. The researchers designed also the GSM-based secure cellular communication link, as well as the software package for the telemedicine center, where the physicians could analyze the received data from the wrist-worn device in greater detail. The AMON prototype was innovative in that it included many miniaturized sensors all integrated through nonstandard placement in a wrist-worn part and in that it also included evaluation software for real-time processing and analysis of the measured vital signs. The development of the AMON wearable health-monitoring device aimed at high-risk cardiac/respiratory patients who would be confined to the hospital or their homes.

After the processing of the raw data, a classification of normal, deviant, risk, high risk, or error was derived as an estimation of the patient's health condition using specific limit values for each vital sign, taken from the World Health Organization. According to the estimated condition, appropriate actions were made from the device, like initialization of additional measurements for validation/re-estimation, risk alarms, transmission of data to the medicine center, etc. Although the conducted validation study revealed problems regarding the reliability of the measured data and the wearability of the device, the general idea of the device was very well received by the users.

Lin *et al.* [21] describe the development of a real-time wireless physiological monitoring system (RTWPMS), which is based on a digital, low-power second generation cordless phone and a custom made medical examination module measuring blood pressure, heart rate, and temperature. A GPS module is also incorporated and sensor interfacing is done through serial ports. System architecture includes also a wireless base station (handles physical transmission/reception of messages/commands), a voice/data exchange device (processes data and commands) and a network management center for overall system control. Conducted tests with system in nursing centers and hospitals validated its ability to transfer voice and data end-to-end at low error rates from multiple sources simultaneously. However, the wearable examination system is too bulky for ambulatory and continuous monitoring and the utilized RF technology is outdated, as identified by the authors as well.

LifeGuard [22] is a multiparameter wearable physiological monitoring system for space and terrestrial applications, whose core element is a crew physiologic observation device (CPOD), which is capable of measuring two ECG leads, respiration rate via impedance plethysmography, heart rate, oxygen saturation, body temperature, blood pressure, and body movement. Typical off-the-shelf sensors are use for measuring most of the biosignals, which are interfaced through wired connections to CPOD data logger that can either send the data via Bluetooth to a base station or record them for 9 h continuously on a memory card. The data logger is based on a PIC μC and uses 2 AAA batteries. The authors conducted a series of verification and validation tests at extreme environments and tested the ability of satellite transmission of collected data with the obtained results indicating acceptable accuracy for the collected data and real-time transmission of measurements to remote locations.

A prototype portable system capable of measuring phonocardiography (PCG), electrocardiography, and body temperature is described in [23]. The developed system consists of a capacitor-type microphone inserted on a stethoscope for PCG detection, a three-lead ECG, a temperature sensor, a measuring board including a CPU, a Bluetooth transceiver, and an A/D module and a PDA with an external memory unit. The functionality of the whole system is controlled by the PDA user by issuing commands to the measuring circuit. The insufficient computational power of the PDA is said to enforce certain function limitations to the system in terms of PCG and ECG sampling rates. In addition to that, the system consists of too many large sized external components and it is too dependable on the end user (measurements are initiated from the PDA, not automatically or event-driven), making it impractical and uncomfortable for long-term unobtrusive monitoring of a patient's vital signs.

Finally, the development of a medical wearable device targeting brain-injured children is described in [24]. The medical device is able to measure blood oxygen saturation and heart rate through a finger-placed pulse oximeter, respiration rate by using a piezoelectric sensor placed on a belt worn on the chest and body movement by using a dual axis thermal accelerometer. The measured data are stored into a multimedia card, which are in turn transmitted at prescribed time intervals through Bluetooth to a home PC. From the home PC, the data are finally transmitted through an ADSL Internet connection (or UMTS) to the Medical Service Center. The implemented system aims at detecting events such as nocturnal apnea, but has the disadvantage of low wearability due to the wired connections between the individual sensors and the wearable Bluetooth module, while no validation tests have been performed as in the case of the previously discussed system.

2) Systems Based on Smart Textiles: Systems in this category are based on a vest or T-shirt with biosensors integrated on the garment.

The MyHeart project supported by the European Commission and involving 33 partners from 10 different countries, including industrial partners such as Philips, Nokia, Vodafone, and Medtronic, aimed at fighting cardiovascular diseases (CVD) by prevention and early diagnosis [25]. It adopted the use of smart clothes, where the sensing modules are either garment-integrated or simply embedded on the piece of clothing [26], [27]. The underlying concept relies on the use of tiny conductive wires knitted like normal textile yarns. In that way, the wearable system is very comfortable for the user, no wireless modules are needed for the sensors and the whole system needs only one centralized on-body power supply, thus resulting in significant decrease of the overall system's size. One main device is used to control the on-garment bus and is also responsible for the synchronization and the power supply for all the on-body components. The developed textile-sensors include an ECG and an activity sensor. An algorithm capable of classifying the activity into resting, lying, walking, running, and going up/downstairs has been implemented, with very high accuracy. Finally, the MyHeart project developed heart belts as well, that could be worn across the chest or attached to a standard bra or to the waistband of standard underwear [28].

The Wearable Health Care System (WEALTHY) project, part of the fifth framework program of the European Commission and completed in 2005, has developed a wearable garment, covering the whole upper body and worn under normal clothing, capable of recording biomechanical variables and physiological signals [29]. The WEALTHY system targets clinical patients during rehabilitation and other high-risk patients, such as elderly people, individuals with chronic diseases and others. The sensor elements, which have been integrated in fabric form (using conducting and piezoresistive materials) on a textile structure [30], [31], are able to monitor a three-lead ECG, EMG placed on the arms, thoracic and abdominal respiration rate, body position and movement, skin, and core temperature. On demand, measurements of blood pressure and oxygen saturation can also be obtained. The wearable garment incorporates also an analog and digital signal-processing module with GPRS or Bluetooth wireless transmission capabilities. Algorithms to remove artifacts introduced in the measured signals by motion have also been implemented, along with the ability to generate alert messages and synoptic patient tables.

MagIC [32], developed by researchers in Milan, Italy, is a washable sensorized vest including fully woven textile sensors for ECG and respiration rate monitoring and a portable electronic board, which evaluates the wearer's motion level and is responsible for signal preprocessing and data transmission through Bluetooth to a local PC or PDA. The wearable system incorporates also skin temperature sensors and it mostly aims at use from elderly people or cardiac patients for home monitoring, enabling, however, also ambulatory daily life health monitoring. The data collected from the evaluation tests performed, showed that the system achieves very good acquired signal quality (except in the case of maximal physical activity) and that it is also able to correctly identify atrial fibrillation episodes and atrial and ventricular ectopic beats.

The Medical Remote Monitoring of clothes (MERMOTH) project, completed in 2006 and is also a European IST FP6 program and part of a wider group of six other European Projects in Smart Fabrics and Interactive Textiles [33], has produced a low cost, knitted, comfortable, and stretchable sensing garment [34]. The developed garment incorporates conductive and electrostrictive fabrics and yarns and dry electrodes, enabling the measurement of ECG, respiratory inductance plethysmography, skin temperature and activity through accelerometers. A PDA is connected to the microcontroller that is used to interface with the sensors on the garment, providing an RF link to a local PC for display and measurement interpretation.

Finally, Pandian *et al.* in [35] describe Smart Vest, a wearable physiological monitoring system that consists of a vest, which uses a variety of sensors integrated on the garment's fabric to simultaneously collect several biosignals in a noninvasive and unobtrusive manner. The parameters measured are ECG, photoplethysmography (PPG), heart rate, blood pressure, body temperature, and galvanic skin response (GSR). Furthermore, it is stated that the ECG can be recorded without the use of gel and that its recording is free of baseline noise and motion artifacts due to hardware-implemented high pass, low pass, and notch filters. Moreover, blood pressure is calculated noninvasively via PPT, where the implemented detection algorithm is individually calibrated based on the user's ECG. Provided results from validation tests confirm to the most part the author's claims regarding the accuracy of the measured physiological parameters. Furthermore, the sensors are connected to a central processing unit, which is capable of correlating the acquired measurements to derive an overall picture of the wearer's health.

3) Mote-Based BAN: In this section, we take a look at WHMS that employ motes, e.g., wirelessly enabled tiny nodes, to form a BAN, where every mote is responsible for collecting one or more types of physiological data and transmitting them to a central node or base station. For a more detailed review of BANs the reader should refer to [4].

In [36], the development of a prototyped wearable wireless body area network (WWBAN) is described. The proposed system consists of common off-the-self wireless sensor platforms using ZigBee (IEEE 802.15.4) compliant transceivers and ultra low-power microcontrollers. Custom sensor platforms, that perform data collection and preprocessing and that are equipped with accelerometers or bioamplifiers for ECG or EMG, have been developed and have been integrated on the commercially available Telos platforms from Moteiv, which use the event-driven TinyOS operating system. The lack of standardization in platforms, system software support, and wireless communication for WBANs is underlined and discussed throughout this paper. Furthermore, as a means of addressing the issue of limited power resources on the motes and extending their operational lifetime, the authors propose to perform on-board advanced signal processing of the acquired biosignals to reduce the wireless transmission duty cycle, and thus the power consumption as well. However, limited computing resources, real-time signal processing requirements and limited memory space make this task even harder.

Researchers in Harvard University have developed CodeBlue [37], a medical sensor network platform for multipatient monitoring environments based on the ZigBee compliant MicaZ and Telos motes, including custom designed biosensor boards for pulse oximetry, three-lead ECG, EMG, and motion activity. The Codeblue project also addressed issues of reliable communication between medical sensors, multiple receivers (PDA's carried by doctors and nurses) and various high data rates. In that direction, a software framework has been implemented, which provides protocols for device discovery, publish/subscribe multihop routing, and a simple query interface allowing end users to dynamically request specific data from a specified network node. Besides that, CodeBlue uses an RF-based localization system, to track the location of patients and caregivers. The system was evaluated in a 30-node testbed in terms of network metrics such as packet loss, fairness across multiple paths, etc., indicating that further work on reliable communication, bandwidth limitation issues and security is needed.

A BAN based on the IEEE 802.15.4 protocol is presented in [38]. The BAN follows a star topology and it is formed of two main types of devices: 1) sensor communication modules (SCM), which are able to interface with both analog and digital sensors; and 2) a personal data processing unit (PDPU), which is in charge of coordinating the BAN, controlling the communication with all the SCMs as well as the communication with external networks (via USB, Wi-Fi, or GPRS). Synchronization in the BAN is handled via the protocol-supported beacon primitives, which are also used to carry commands about sensor configuration parameters (sampling rate, gain, etc.), sensor activation/deactivation and data transmission. The SCMs are 802.15.4 compliant prototypes, designed as a four-layer PCB and the PDPU (powered by a lithium-ion rechargeable battery) is also a custom design, which includes an ARM Thumb Processor, a GPRS modem, a Wi-Fi module, a Security Digital memory card, a simple two-line LCD display and a five-button-based joystick. The firmware of the PDPU is an embedded Linux OS. Employed biosensors include a sensor recording arterial blood pressure, microelectrodes for ECG measurement, position sensors, and respiration sensors.

Chung *et al.* [39] present a custom developed u-healthcare system, which consists of custom 802.15.4 capable nodes that interface with ECG and blood pressure sensors as well as with a basic cell phone device for data display and signal feature extraction. The novelty of the projects consists in transmitting only identified suspicious ECG and BP patterns to the hospital's server. This is done by first extracting simple ECG features (such as QRS duration, RR interval, R magnitude, etc.) and making a decision based on simple if-then-else rules. In the same manner, blood pressure measurements extracted from a wrist-sensor are transmitted as well in case they are found to be out of range. In [40], Chung *et al.* present more details regarding the hardware of the ubiquitous sensor nodes (USN), which are also extended to include accelerometers and SpO2 sensors.

Other research projects that utilize Zigbee motes for BANs include: 1) the BAN described in [41], where researchers have included ECG, PPG, and PCG sensors and have implemented a synchronous sampling mechanism for data synchronization; 2) WiMoCA [42], developed by researchers in Italy. A star topology network is formed by sensor nodes with a palmtop PC functioning as a base station and which aims at posture recognition, gait pattern recognition, and balance detection applications; 3) Bi-Fi [43], an embedded sensor/system architecture for wireless biosignal recording, employing ECG, EEG, and SpO2 sensors, where the main goal is to perform on-board DSP to remove the bandwidth bottleneck imposed by the transceiver; d) BASUMA [44], which uses sensors equipped with the ZigBee compliant Philips AquisGrain platform. It aims at long-term monitoring of chronically ill patients and uses several custom noninvasive sensors for monitoring parameters such as ECG, air, and blood content of the thorax, body temperature, breathing rate and cough control, blood pressure, pulse rate, and oxygen saturation; e) a body sensor network earpiece [45], which includes a pulse oximeter and a 3-D accelerometer and which aims at monitoring postoperative recovery at home in patients undergoing abdominal surgery. The proposed device is based on the BSN node, developed from the Department of Computing in Imperial College and it includes intelligent algorithm for recognizing the type and the intensity of the user's activity.

Besides Zigbee, other technologies have been utilized for BANs. For instance, in [46] the authors propose the use of intrabody communication for exchanging information between wearable electronic sensors within a BAN. To validate that claim, a prototype transmission system is constructed using aluminum electrodes powered by a 3 V dc source and operating in the 10.7 MHz frequency modulation (FM) band. The communication module was interfaced with a finger-tip pulse oximeter measuring heart rate and oxygen saturation in blood and transmitted the sensed data over a distance of 30 cm. The illustrated results indicate acceptable communication quality, but probably insufficient reliability for types of data requiring high accuracy and low distortion.

Yuce *et al.* [47] presented a recently developed wireless body sensor network hardware, which uses the recently allocated medical implant communication service (MICS) band. The system prototype consists of a pulse rate and a temperature sensor, a central control unit (CCU), and a receiver station at a medical center. The developed system has overall very small size and cost and can achieve very low power consumption. However, the latter is accomplished by keeping the sensor nodes in sleep node most of the time (one measurement every 5 or 10 min) and by using a polling approach to acquire the data.

Finally, Human++, a research project in the Netherlands, has developed a BAN consisting of three sensor nodes and a base station [48]. Each sensor node is responsible for acquiring, amplifying, filtering, processing, and wirelessly transmitting multichannel signals of ECG, EEG, and EMG, while the base station functions as a data collector in star topology, regulating the information flow. The developed system is able to run autonomously for 3 months on two AA batteries. In addition to that, Belgium research center IMEC has developed a very promising prototype of a body-heat powered autonomous pulse oximeter [49], powered completely through a wrist-worn, watch-size, thermoelectric generator which transforms the wearer's body heat into electrical energy and uses, instead of a battery module, a supercapacitor for short-time energy storage.

4) WHMS Based on Commercial Bluetooth Sensors and Cell Phones: The first example in this category is HealthGear from Microsoft [50]. The prototype released so far consists of a noninvasive blood oximeter, a sensing board providing the sampled oxygen saturation and heart rate signals, a Bluetooth module for wireless transmission of the measured signals, AAA battery power supply and a cell phone to provide the user interface. This current exemplary application aimed at monitoring users during their sleep to detect sleep apnea events. Two methods for the automated detection of sleep apnea events are proposed. The first one works in the time domain and detects apnea events after statistically evaluating threshold values for the oxygen saturation level, while the second one works in the frequency domain trying to detect peaks in a filtered periodogram of the oximetry signal.

The system was evaluated by 20 individuals and according to the results, there were no technical problems and the system was completely successful in detecting mild and severe obstructive sleep apnea (OSA). The users also reported that the wearability and the functionality of the whole system were good. However, the measurements taken were not compared with a polysomnograph for validating the results.

HeartToGo [51] is a cell phone-based wearable platform, capable of continuously monitoring the user's ECG signal via a wireless ECG sensor, of analyzing the electrocardiogram in real time and possibly detecting any abnormal patterns pertaining to cardiovascular disease. The proposed system is able to adapt to the individual user's physiological conditions through the use of artificial neural network—based machine learning schemes, which can possibly result in more accurate classification of ECG patterns.

Leijdekkers and Gay [52] have developed a heart attack self-test application implemented on a personal health monitor system that includes a conventional mobile phone and a Bluetooth enabled ECG sensor. The mobile phone serves the function of analyzing the streaming data from the sensor in real-time and transmitting them to a heart specialist. In the illustrated application, a simple user interface on the phone is used to acquire feedback from the user about his symptoms and in case the patient's health condition is found to be at risk, based on his answers, the emergency services will be contacted.

Another Bluetooth personal area network (PAN) approach is described in [53], where researchers have employed a smartphone to collect physiological data from Bluetooth-enabled sensors (a pulse oximeter and a GPS module), to detect alarming conditions and to transmit the encrypted data via GPRS or Wi-Fi. Similarly, the Mobile Care System with Alert Mechanism presented in [54] utilizes a Bluetooth blood pressure monitor and ECG sensor and a mobile phone as the processing core for symptom recognition and alert message generation based on different urgency levels.

Finally, the work described in [55] presents a wearable device for continuous ECG monitoring, where the ECG sensor continuously transmits the measured and amplified ECG signal to the hand held device (HHD), which is a common PDA. The PDA serves as the "intelligent" device of the system, in that it processes, analyzes and saves the recorded ECG measurements. An algorithm for detecting arrhythmia events, is implemented on the HHD, which has also a documented true detection rate of 99.2%. The HHD communicates via GPRS with a remote clinical station, transmitting alarm signals along with the recorded ECG waveforms. The doctor at the station end can setup the limits for the specified alarm detections, such as bradycardia, tachycardia, and arrhythmia. When an abnormal ECG activity is detected, the HHD will record 1 min of the ECG signal and transmit it to the base station and it will also calculate heart rate and some other parameters based on the measured waveform.

5) Other Types of WHMS: In this last subcategory of research prototypes, we will take a look at some interesting wearable systems that could not be directly classified to one of the previous categories.

Such a system is AUBADE [56], developed from the University of Ioannina in Greece, a wearable system that performs evaluation of the emotional state of an individual targeting environments, where human subjects operate at extreme stress conditions. The developed prototype consists of a mask containing sixteen EMG textile fireproof sensors, a three-lead ECG and respiration rate sensors located on the chest of the subject and a textile sensor measuring electrodermal activity (or galvanic skin response or skin conductance activity) placed inside a glove. A 3-D facial representation mechanism and an intelligent emotion recognition module have also been implemented classifying the individual's psychological condition from a set of emotions.

Another interesting effort is described in [57], where the authors describe a system that uses a wearable ECG device to detect the motion artifacts (distortions) and classify the type of body movement activity (BMA) from the ECG signal itself. This novel study targets situations where dynamic heart monitoring is required, e.g., in case of mobile patients. The preprocessed ECG beat observations are used by a supervised learning approach, based on principal component analysis (PCA), to train the BMA classifiers for sitting still, up and down, movement of left, right or both arms, walking on a level floor, and climbing stairs up and down.

A wearable system for measuring emotion-related physiological parameters has been developed at Fraunhofer IGD Rostock [58]. It uses a glove as garment hosting a sensor unit that collects data from skin conductivity and skin temperature sensors and a conventional chest belt from Polar as a heart rate sensor. The sensor unit communicates wirelessly using an ISM band transceiver with a base station, which can generate events, such as detection of certain physiological states, although this process is not described in the current study. The reader interested further in glove-based systems and their applications should refer to the comprehensive study of such systems presented in [59].

B. Commercially Available WHMS

In this final category of WHMS, we will briefly discuss several commercially available wearable systems for health-monitoring application.

For example, a lot of manufacturers like Nonin [60], Philips [61], Nellcor [62], Agilent [63], Redding Medical [64], and others are providing small, wearable, low cost, and lightweight finger-tip pulse oximeters, that provide real-time display of measured heart rate and blood oxygen saturation. Other examples are the heart rate monitors manufactured from Polar [65] and Omron [66], which use a chest worn belt and wristwatch for display of measurements.

Other commercial systems include Vivago WristCare [67], a wrist-worn device, which monitors skin temperature, skin conductivity and movement. A similar device is the SenseWear Armband developed from BodyMedia [68], which in addition monitors ambient temperature and heat flow. Both devices include a wireless transmitter for communicating the collected data and possible alarms to a base station for further evaluation by a professional clinician.

WelchAllyn has developed the Micropaq Monitor [69], a wearable device worn in a carrying pouch, which can perform pulse oximetry and up to five-lead ECG monitoring. Another example of commercially available health monitoring systems is the portable polysomnography systems from CleveMed [70], which collect multiple channels of EEG, ECG, EMG, EOG, airflow, snore, thoracic and abdominal respiratory efforts, body position, and pulse oximetry and can transmit the measured data wirelessly to any location by using a simple ISM band transmitter.

VivoMetrics has developed LifeShirt [71], a washable lightweight vest that includes respiratory rate sensors, one-lead ECG for heart rate measurement and an accelerometer for activity monitoring. Foster–Miller's Watchdog [72] physiological monitoring tool is a garment-based system capable of monitoring heart rate, respiration rate, posture, activity, skin temperature, and GPS location. Another example is the SmartShirt [73] system from Sensatex, a T-shirt-based wearable system using conductive fiber sensors to measure ECG, respiration rate, and blood pressure.

CardioNet has developed a mobile cardiac outpatient telemetry system (MCOT) for ambulatory ECG monitoring, aiming at helping physicians diagnose and treat patients with arrhythmias [74]. Other products include the Bioharness monitor from Zephyr, Inc. [75], a chest belt that monitors ECG, respiration rate, skin temperature and activity, and is wirelessly enabled, and the SpO2, ECG, and glucose wireless sensors from Alive Technologies [76]. Furthermore, Schiller [77] and Corscience [78] have also developed small portable Bluetooth ECG monitors.

V. Maturity Evaluation

In this section, we attempt to evaluate the most representative and "prevailing" systems from the ones discussed in the previous sections. The choice of the systems to be evaluated was based upon the following:

1) their ability to measure multiple parameters;
2) the amount and the detail level of their provided documentation;
3) the frequency of their citation by other projects;
4) the extent to which they utilize state-of-the-art hardware technologies; and
5) the incorporation of intelligent algorithms for feature extraction and/or decision support.

The systems that have been chosen for evaluation are listed in Table III along with a description of their hardware and communication modules, the physiological parameters they measure and their stated application field.

Several features have been chosen for the evaluation of the various wearable systems in Table III. In Table IV, a list of these features is provided along with a brief description for each one. The choice of features was based upon the wide range of requirements a wearable biosensor system must meet in order for it to be used in real-life health-monitoring scenarios. Since in the general case there are no ideal objective metrics for evaluating each feature of every system, the evaluation has been done with relevance to the top approach in each category. In addition to that, we wanted to provide an overall evaluation of the systems based on the perspective of the parties who are involved in the development and the use of the systems, e.g., the manufacturers, the doctors, and the users. The reason for doing that is because specific features may have different significance levels for each interested party, for example the on-board computing resources of the system may be a feature that is highly important to the developer of the system, while it may not be that important to the user who would be naturally more concerned about the ease of use of the WHMS. Therefore, after extended discussions with colleagues, department's students, and doctor acquaintances, we decided to grade the importance of each feature as low (1), medium (2), or high (3), which resulted in an average weight for every feature depicting its importance in the evaluation of a WHMS. These weights are presented in Table V.

TABLE III
SELECTED WHMS

Project Title/Institution	Hardware Description	Communication Modules	Measured Signals*	Medical applications
A) LiveNet (MIT) [19]	PDA, microcontroller board	wires, 2.4GHz radio, GPRS	ECG, BP, R, T, Sa02, EMG, GSR,	Parkinson symptom & epilepsy seizures detection, behav. modelling
B) AMON (EU IST FP5 program) [20]	Wrist-worn device	GSM link	ECG, BP, T SaO2, A	High-risk cardiac-respiratory patients
C) LifeGuard (Stanford Un.& NASA) [22]	Custom μC-based device & commercial bio-sensors	serial cables, Bluetooth	ECG, BP, R, T, SpO2, A	Medical monitoring in extreme environments (space & terrestrial)
D) MyHeart (EU IST FP6 program) [25]-[28]	PDA, Textile & electronic sensors on clothes + heart belt	conductive yarns, Bluetooth, GSM	ECG, R, other vital signs, A	Prevention and early diagnosis of CVD
E) WEALTHY (EU IST FP5 program) [29]-[31]	Textile & electronic sensors on jacket	conductive yarns, Bluetooth, GPRS	ECG, R, T, EMG, A	Monitoring of rehabilitation & elderly patients, chronic diseases
F) MagIC (Un. Of Milan, Italy, Bioeng. Centre & Cardiac Rehab.Unit) [32]	Vest with textile sensors, custom electronioc board, PDA	Bluetooth	ECG, R, T	Recording of cardiorespiratory and motion signals during spontaneous behavior in daily life and in a clinical environment
G) MERMOTH (EU IST FP6 program) [33],[34]	Garment with knitted dry electrodes, PDA	conductive yarns, RF link	ECG, R, T, A	General health monitoring
H) Smart Vest (National Pr. On Smart Materials, India) [35]	Vest with woven sensors, microcontroller	woven wires, 2.4 GHz ISM RF	ECG, BP, T, PPG, GSR	General remote health monitoring
I) CodeBlue (Harvard Univ.)[37]	Sensor motes with custom processing boards	Zigbee	ECG, SpO2, A	Real-time physiological status monitoring with wearable sensors
J) Body area network (Valencia,Spain&Malta Un.& Microvitae Tech)[38]	Zigbee-based motes & Zigbee-based custom base device	Zigbee, Wi-Fi, GPRS	ECG, BP, R	Detection & prediction of human physiological state (wakefulness, fatigue, stress) during daily activities
K) WSN u-Healthcare system (Dongseo Un. Korea) [39],[40]	Custom tiny motes, cell phone & commercial sensors	Zigbee, CDMA	ECG, BP, SpO2, A	Health monit. and remote identification of suspicious health patterns for further evaluation by physicians
L) Human++ (IMEC) [48], [49]	Miniature low-power BAN nodes, energy scavenging	Zigbee	ECG, EEG, EMG	Enable autonomous wearable sensor networks for general health monitoring
M) HealthGear (Microsoft) [50]	Custom sensing board, comm.. sensors and cell-phone	Bluetooth	HR, SpO2	Monitoring users during their sleep to detect sleep apnea events
N) HeartToGo (Un. of Pittsburgh) [51]	Cell phone & comm. available BT bio-sensors	Bluetooth, GPRS	ECG, A	Individualized remote CVD detection
O) Personal Health Monitor (Un. of Tech. Sydney) [52]	Cell phone & comm. available BT bio-sensors	Bluetooth, GPRS	ECG, BP, A	Heart-attack self-test for CVD patients
P) Wearable ECG, arrhythmia detection (Eng. + Med. Dpts, Norway) [55]	Microcontroller board, PDA	wires, Zigbee, GPRS	ECG	Remote detection of cardiac arrhythmias
Q) AUDABE (Dept. of Medical Physics, Ioannina, Greece) [56]	Mask, glove, chest sensors	wires, Bluetooth, Wi-Fi	ECG, R, GSR, EMG	Evaluation of the emotional state of an individual at environments where subjects operate at extreme stress conditions
R) Lifeshirt (Vivometrics) [71]	Sensors embedded in vest, PDA	Bluetooth & wires	ECG, R, A	All-day remote health monitoring
S) Bioharness (Zephyr Inc) [75]	Chest Belt	Bluetooth or ISM RF	ECG, R, T, A, P	Remote monitoring of human performance and condition in the real-world

*ECG: electrocardiogram (also implies the measurement of heart rate), HR: heart rate, EMG: electromyogram, BP: blood pressure, R: respiration, T: temperature, P: posture, GSR: galvanic skin response, A: activity, PPG: photoplethysmography.

Finally, an overall maturity score was produced for every system in Table III based on the evaluation of every feature of each system under consideration and by producing a weighted average score according to the weights depicted in Table IV. It should be noted that the maturity score of a system corresponds to the level to which the system fulfills its potentials regarding its available resources and design approach. Therefore, a higher average score corresponds to a system that has both reached a top level of development and also meets the requirements listed in Table IV to the fullest. The corresponding scores are shown in Fig. 2. We would also like to stress the fact that the purpose of this maturity evaluation is not to criticize the developed systems, but to identify their development level according to their potentials and to provide possible direction for further research in the fields that these systems show a lack of performance.

VI. DISCUSSION

As it can be seen from Fig. 2, none of the systems reached what was set as the maximum maturity level. However, from the systems we considered in this paper, there are several ones that achieved relatively high scores. These include systems based on smart textiles, which have the advantage of high wearability and comfortableness to the user and which can achieve a high degree of reliability due to guaranteeing good contact between the skin and the biosensors even when the subjects are in motion. In addition to those types of systems, the HeartToGo project [51]

TABLE IV
EVALUATION FEATURES

Wearability (F1)	The system must have low weight and size.
Appropriate placement on the body (F2)	The system has to be unobtrusive and comfortable, in order not to interfere with the user's movements and daily activity.
Aesthetic issues (F3)	The system should not severely affect the user's appearance.
Data encryption and security (F4)	Encrypted transmission of measured signals and authentication requirement for private data access.
Operational lifetime (F5)	Ultra low power consumption for long-term, maintenance-free health monitoring.
Real Application (F6)	The developed system is applicable (and useful) to real-life scenarios/health conditions.
Real-time Application (F7)	The wearable system produces results, e.g. display of measurements, alerts, diagnosis etc, in (or near) real-time.
Computational & Storage Requirements (F8)	The computational and storage resources required or utilized by the system to achieve desirable results.
Ease of use (F9)	The system incorporates a friendly, easy-to-use and easy-to-learn user interface.
Performance and test in real cases (F10)	Sufficient results and performance statistics are provided to verify the system's functionality in real cases.
Reliability (F11)	The system produces reliable and accurate results.
Cost (F12)	The amount of money required to produce and purchase the proposed wearable system.
Interference Robustness (F13)	Availability and reliability of wirelessly transmitted physiological measurements.
Fault Tolerance (F14)	The system produces reliable results under any circumstances, such as various kinds of patient's movements.
Scalability (F15)	Potentiality of upgrading, enhancing and easily incorporating additional components to the developed system.
Decision Support (F16)	The implemented system includes some type of diagnosis/decision mechanism or an algorithm/pattern recognition system for context aware sensing of parameters.

TABLE V
FEATURES' WEIGHTS

	Patient's perspective	Physician's perspective	Manufacturer's perspective	Average
F1	3	2	1	2
F2	3	2	1	2
F3	3	1	2	2
F4	2	3	3	3
F5	3	2	2	2.3
F6	3	3	3	3
F7	3	2	2	2.3
F8	1	1	3	1.7
F9	3	2	1	2
F10	3	3	3	3
F11	3	3	3	3
F12	3	1	3	2.3
F13	2	3	2	2.3
F14	3	3	3	3
F15	2	2	2	2
F16	3	2	2	2.3

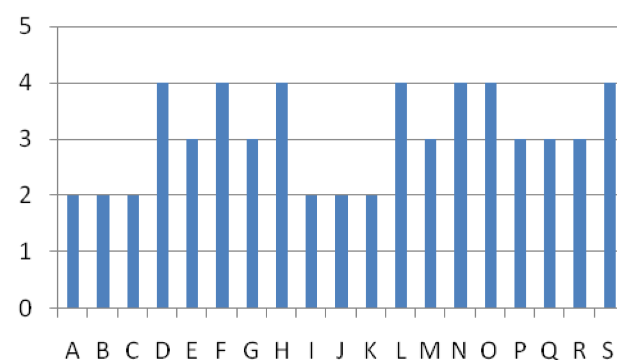

Fig. 2. Maturity scores for the systems listed in Table III (1 = low, 2 = medium-low, 3 = good, 4 = high, 5 = maximum).

and the Personal Health Monitor [52] reveal also a promising alternative to the design of WHMS, as they leverage commercial cell phone devices and commercially available biosensors to set up a system that is either able to interact with the user to get additional feedback about his health-status or to adapt to his/her individual medical history by means of artificial neural networks.

However, there have been identified several common issues with the evaluated systems and which constitute a set of challenges that will need to be addressed by further researchers in order to improve the efficiency, the reliability, and the security of WHMS. These challenges include:

Battery technologies and energy scavenging: Power consumption (and battery size) appears to be perhaps the biggest technical issue and performance bottleneck in current implementations. Wearable biosensor systems should be able to operate maintenance-free for long periods (e.g., years). Further research in power scavenging techniques (through body heat or motion), low-power transceivers and improvements in battery technologies promise to solve this problem.

Security of private information: The information collected about the user, describing his health status, has to remain secure and not be allowed to be disclosed to anyone besides to the system's wearer and to the supervising physicians. Thus, proper encryption and authentication mechanisms are required to ensure the privacy of all the communicated data (sensor-to-sensor communication in the BAN or wearable system to base station transmissions).

Further improvements in sensor miniaturization and efficiency: In general, a lot of the biosensors used in current wearable systems tend to have bulky size and may require very specific on-body placement or body postures to provide reliable measurements. Further improvements in textile sensors and advanced sensor design and miniaturization are required to appropriately address these shortcomings.

Clinical validation: Developed systems must be exhaustively tested and validated by professional physicians.

Standardization and cooperation at all levels: The requirement for interoperability between different communication infrastructures and between various types of devices, sensors, actuators, health providers, etc., underlines the need for standardization in communication interfaces and cooperation between researchers, medical experts, hardware and textile manufacturers, network providers, and other health organizations.

VII. Conclusion

This paper reviewed the state-of-the-art in research and development of wearable sensor-based systems for health monitoring. As it is shown by the current technology status, WHMS have the potential to revolutionize healthcare by providing low-cost solutions for ubiquitous, all-day, unobtrusive personal health-monitoring and are expected to enable early detection and better treatment of various medical conditions as well as disease prevention and better understanding and self-management of chronic diseases. However, the current study highlights the fact that there are still a lot of challenges and issues that need to be resolved for wearable systems to become more applicable to real-life situations and also to become accepted by patients and other users as a reliable, multifunctional, easy-to-use, and minimally obtrusive technology that can increase their quality of living.

Our research group is working on developing a new WHMS, termed Prognosis [79], [80]. In the prototype under development, we look to address the issues of patient–system interaction and individual pattern history extraction and adaptation, in order to address the weak features of a wearable system's unfriendliness and the system being disease-specific instead of patient-specific, which is what would be ideally desired.

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