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A Survey on Wearable Biosensor Systems for Health Monitoring

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Abstract— **Wearable biosensor systems for health monitoring are an emerging trend and are expected to enable proactive personal health management and better treatment of various medical conditions. These systems, comprising various types of small physiological sensors, transmission modules and processing capabilities, promise to change the future of health care, by providing low-cost wearable unobtrusive solutions for continuous all-day and any-place health, mental and activity status monitoring.**

This paper presents a comprehensive survey on the research and development done so far on wearable biosensor systems for health-monitoring, by comparing a variety of current system implementations and approaches and identifying their technological shortcomings. A set of significant features, that best describe the functionality and the characteristics of wearable biosensor 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 current achievements and their maturity level and to provide direction for future research improvements.

I. INTRODUCTION

DURING the past decade there have been numerous research and development efforts in the field of wearable health-monitoring systems motivated by the need to monitor a person's health status outside of the hospital [1]-[3]. Such a system can provide real-time feedback information about one's health condition, either to oneself or to a professional physician at the hospital or even alert the individual in case of possible imminent health threatening conditions. Furthermore, wearable biosensor systems offer also a great alternative to deal with increasing health care costs and also to address the issues of managing and monitoring chronic diseases, elderly people, postoperative rehabilitation patients and persons with special abilities [4].

Wearable systems for health monitoring consist of several miniature sensors, wearable or even implantable. The sensors measure significant physiological signals like heart rate, blood pressure, body and skin temperature, ECG etc. These measurements are communicated usually through a wireless link to a central node, for example a PDA or a microcontroller board, which may then in turn transmit the data to a clinician or display the according information on a user interface and possibly generate alert signals. The previous demonstrate a possible wearable medical system scenario which can involve the following system components: sensors, materials, smart textiles, actuators, power supplies, wireless communication abilities, control and processing units, interface for the user, software and advanced algorithms for feature extraction and decision support. In Fig.1, a system architecture that could apply to such a scenario is presented.

Fig.1 visualizes the concept of a possible wearable system and should not be perceived as a standard system design, as many systems may adopt significantly varying architectures (for example bio-signals may be transmitted in analog form and without preprocessing to the central node and bidirectional communication between sensors and central node may not exist).

Wearable systems for health monitoring need to satisfy a great variety of criteria and constraints. These include small weight and size, privacy of medical data, unobtrusiveness, ease of use, low cost, reliability and low power consumption to name the most important ones. As a result, 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.

This paper briefly reviews the state-of-the-art in research and development on wearable low-cost unobtrusive systems for health-monitoring by identifying and comparing the attributes of the most promising current achievements of several worldwide projects. The paper concludes with a discussion of the current shortcomings in system design, integration and functionality along with other challenging issues that have to be overcome in order for wearable systems to become more efficient and applicable as real-life solutions, which can potentially increase the quality of life.

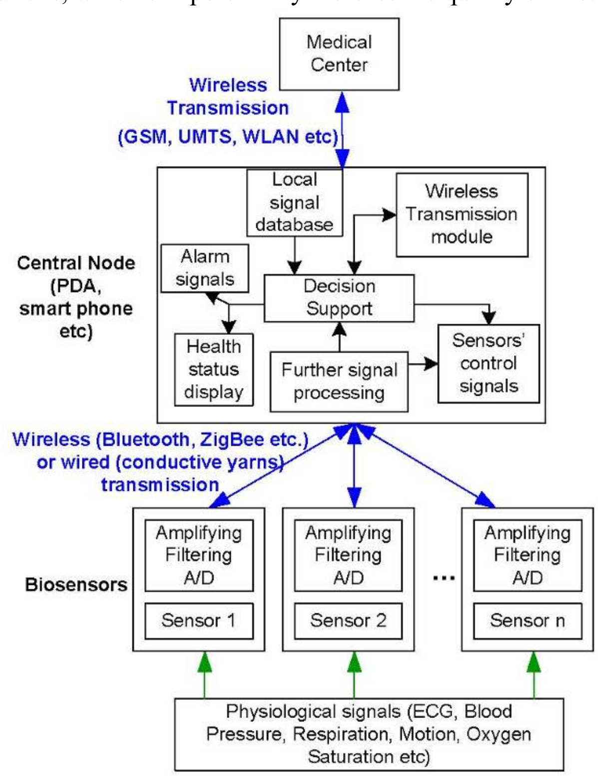

Fig.1 An architecture of a wearable health-monitoring biosensor system.

II. Review

A) Survey Features

Several features have been chosen for the evaluation of the various wearable systems discussed in the current survey. 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. In Table I, all the chosen features are listed along with a brief explanation for each one.

B) Survey Tables

In Table II for each one of the selected features a weight is assigned (1-10), which reflects the feature's average importance, taking into consideration the perspective of the patient/wearer, the manufacturer and the possible supervising physician. For example, the system's complexity and computational requirements are not that (or at all) important to the patient as it is to the manufacturer. On the contrary, ease of use is of most importance mainly to the patient.

C) Reviewed Wearable Systems

In Table III all the wearable systems, which were considered and evaluated are listed.

TABLE I
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.
Complexity and Computational Requirements (F8)	The number of operations and computational power required by the system to achieve desirable results.
Ease of use (F9)	The system incorporates a friendly, easy-to-use 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 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 II
FEATURES' WEIGHTS

	Patient's perspective	Physician's perspective	Manufacturer's perspective	Average
F1	10	3	5	6
F2	10	3	3	5.3
F3	10	1	5	5.3
F4	8	6	10	8
F5	8	5	7	6.7
F6	10	10	10	10
F7	8	6	3	5.7
F8	1	1	9	3.7
F9	10	7	3	6.7
F10	10	10	10	10
F11	10	10	10	10
F12	5	2	7	4.7
F13	5	6	8	6.3
F14	10	10	10	10
F15	3	3	6	4
F16	10	6	5	7

Finally, in Table 5, all the discussed wearable systems are graded. We grade each feature on a scale of 0-10. If the corresponding cell in the table is left empty, this means that there is not enough information on that characteristic. For each system, a final weighted average score is produced, corresponding to the formula: $(\Sigma_i w_i \cdot x_i)/\Sigma_i w_i$ where w_i is the weight of each feature (Table II) and x_i is the corresponding score (Assigned features' weights and corresponding system scores are based on "aggregated opinions" of colleagues, department's students and doctor acquaintances to reduce the level of subjectivity in these metrics).

TABLE III
WEARABLE BIOSENSOR SYSTEMS

	Project Title or Description	Hardware/ Communication	Measured Bio-signals*
A	HealthGear (Microsoft) [5]	Pulse oximeter and cell phone / Bluetooth	HR, Sa02
B	AMON (EU IST FP5 program) [6]	Wrist-worn device / GSM link	BP, T, Sa02, ECG, A
C	BSN Earpiece, (Imperial College) [7]	Ear-worn device / Zigbee	HR, Sa02, A
D	LiveNet, (MIT) [8]	PDA, microcontroller board / wires, 2.4GHz radio, GPRS	A, ECG, EMG, GSR, T, R, Sa02, BP
E	AUDABE (Dept. of Medical Physics, Ioannina, Greece) [9]	Mask, glove, chest sensors / wires, Wi-Fi, Bluetooth	EMG, ECG, R, GSR
F	BMA classification from W-ECG (Indian Institute of Technology) [10]	Portable ECG device / wires	ECG
G	Wearable ECG, arrhythmia detection (Eng. + Med. Dpts, Norway) [11]	PDA, microcontroller board / wires, Zigbee, GPRS	ECG

H	MyHeart (EU IST FP6 program) [12]	PDA, Textile & electronic sensors on clothes / conductive yarns, GSM, Bluetooth	ECG, R, other vital signs, A
I	Low-Power Wireless Medical Sensor Platform (ECE Dept. Un. Of Colorado at Boulder, USA) [13]	Ultra-low power sensor prototype / 2.4 GHz radio	A, T, GSR
J	Wireless physiological signal measuring system (Nat. Cheng Kung University) [14]	PDA, microcontroller board / wires, Bluetooth	HS, ECG, T
K	WBAN system for ambulatory monitor. (University of Alabama in Huntsville, USA) [15]	Zigbee nodes with custom sensor platforms / Zigbee	ECG, EMG, A
L	Ultra-Wearable, wireless, low power ECG monitoring (Univ. of California, Irvine, CA) [16]	Insulated bioelectrodes, custom sensor node / 2.4 GHz radio	ECG
M	Wearable multi-sensor system for emotion-related data (Fraunhofer Institute, Rostock) [17]	Glove with sensor unit, chest belt / ISM band radio	GSR, T, HR
N	CodeBlue (Harvard University) [18]	Zigbee nodes with custom sensor platforms / Zigbee	Sa02, ECG, A
O	BASUMA (University of Potsdam) [19]	Zigbee-based nodes on chest belt or ear clip / Zigbee	ECG, T, R, BP, Sa02
P	Wireless medical wearable device (EU IST FP5 progr.) [20]	Pulse oximeter, piezoelectric sensor / Bluetooth, UMTS	Sa02, HR, R, A
Q	W-BSN using MICS (Univ. of Newcastle, AUS)[21]	MICS-based implantable prototype sensor / MICS	HR, T
R	WEALTHY (EU IST FP5 program) [22]	Textile & electronic sensors on jacket / conductive yarns, GPRS, Bluetooth	ECG, EMG, R, T, A
S	MagIC (Centro di Bioingegneria, IT) [23]	Vest with textile sensors, custom electronioc board, PDA / Bluetooth	ECG, R, T
T	MERMOTH (EU IST FP6 program) [24]	PDA, knitted dry electrodes / conductive yarns, RF link	ECG, R, T, A
U	Human++ (IMEC) [25]	Miniature low-power BAN nodes, energy scavenging / Zigbee	ECG, EEG,EMG
V	SmartShirt (Sensatex) [26]	Shirt with conductive fiber sensors, PDA / conductive yarns, Bluetooth or Zigbee	ECG, BP, R
W	Lifeshirt (Vivometrics) [27]	Sensors embedded in vest, PDA / Bluetooth,wires	ECG, R, A
X	SenseWear Armband (Bodymedia) [28]	Wrist-worn device / RF link	T, GSR, A HF
Y	WristCare (Vivago) [29]	Wrist-worn device / Bluetooth, GPRS	T, GSR, A

* HR=Heart Rate, Sao2=Oxygen Saturation, ECG=Electrocardiogram, BP=Blood Pressure, A=Activity, R=Respiration, EMG=Electromyogram, EEG=Electroencephalogram, T=temperature (skin or body), GSR=Galvanic Skin Response, HS=Heart Sounds, HF=Heat Flux

TABLE IV
GRADING OF SYSTEMS ACCORDING TO SELECTED FEATURES.

	A	B	C	D	E	F	G	H	I	J	K	L
F1	5	4	4	3	5	3	4	8	6	4	5	9
F2	4	6	7	6			8	9		5		9
F3	5	2	3	2			9	8		3	2	9
F4		5	5				6				6	
F5	3	3	4			4		7	8		4	3
F6	9	9	8	9	9	9	9	9	7	8	7	9
F7	9	9	9	9	9	8	9	9	7	8	5	9
F8	8	7	8	7	6	9	6		8	5	8	8
F9	8	7	6	6	6	4	6	8				5
F10	7	7	6	5		8	4	8				5
F11	7	4	6			5		8				5
F12	9	6	7	5		8		6				
F13		6	5								4	
F14	8	1	5					7				
F15	7	1	2	8	7		8	5	9	7	8	8
F16	8	8	6	8	9	9	8	7				

	M	N	O	P	Q	R	S	T	U	V	W	X	Y
F1	5	7	8	5	8	7	8	8	6	8	9	6	9
F2	5	7	7	7		8	8	8		8	8	7	9
F3	2	7	7	3	6	6	7	6		6	8	3	6
F4		6	6										
F5		4	4	5	7		5		9	5			8
F6	8	8	9	8	9	9	9	9	9	9	9	7	8
F7	9	8	9	8	7	9	9	9	9	9	9	8	9
F8	8	8	7	8	8	8	7	8	8	8	6	7	7
F9	5	5	5	6		8	7	6		8	9	8	8
F10	2	3	5			8	8	6	7	8	8	8	8
F11	8		5			8	8	6	7	7	8	7	6
F12					7	7	6	7		5			
F13		5	4	5									
F14	6				8		6				7	7	5
F15	9	9	9	6	6	4	4	6	9	3	2	1	1
F16				4		7	7				5	6	6

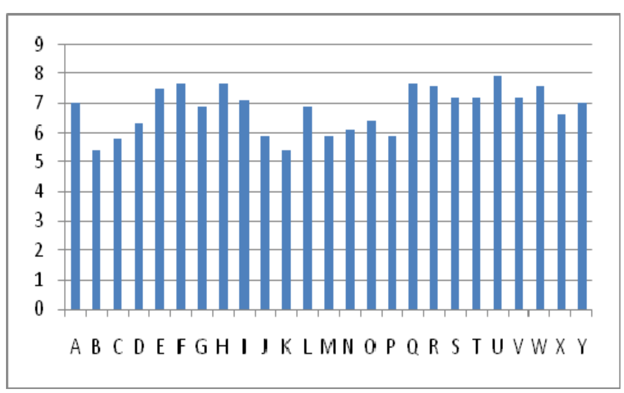

Fig. 2 Average Grading for every system.

III. Discussion and Conclusions

This paper reviewed the state-of-the-art in R&D of wearable biosensor systems. Although it is generally accepted that these systems have the potential to revolutionize health care, by realizing low-cost personal health monitoring [1]–[4], the current study indicates the fact, that there are still a lot of issues that need to be resolved for this technology to become more applicable to real-life situations. The main challenges, which future researchers will need to address, are pointed from the presented evaluation.

Specifically many systems "score" low on wearability, because sensor, battery and on-body hardware size tends to be too bulky. Textile integration of these modules is an efficient alternative approach, but has the disadvantage of being less scalable. Furthermore, power consumption appears to be the greatest performance bottleneck in current prototypes. Future advances in battery technologies and energy scavenging techniques are expected to address this issue. Additionally, widely adopted WPAN standards for Body Area Networks (BAN), such as Bluetooth and Zigbee, perform poorly either in providing Quality of Service (QoS) under interference from other ISM band transmissions or in power-saving for long-term maintenance-free operation. The future IEEE 802.15.6 standard is expected to solve to this problem [30]. Finally, integration of proper encryption and authentication mechanisms is required to ensure privacy and security of personal health data in BANs and in encompassing telemedicine systems.

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