Chapter 1

Introduction

Global expenditure on health care reached 10% of the gross domestic product in 2009 [1]. The development of continuous monitoring services could lead to significant savings in overall medical costs, since it would contribute to reduce hospitalization either through prevention of disease progress or by providing suitable resources for independent living [2].

Wearable technology represents a new emerging field with rising potential influence in several aspects of the modern healthcare sector, particularly in delivering point-of-care services. A wearable sensor is a comfortable and easy-to-use solution specifically designed with built-in electronic functions, for continuously monitoring an individual's health condition [3, 4]. These systems are valuable for many fields of applications (e.g. health monitoring, automotive and aeronautics) since they can provide levels of performance and capacities way ahead of the conventional systems. In addition, they also enhance the quality of life in patients in rehabilitation, chronically ill or disabled [4, 5].

1.1. Wearable Devices

Nowadays, quality of life is supported by medical resources that were not available in the past. The growing demand for wearable devices is being driven by the considerable need for a preventive medicine instead of reactive; the global increase of health awareness and also by the need of a proactive personal healthcare in a daily basis [6, 7].

A wearable medical device is as an unobtrusive, self-sufficient and ubiquitous system that supports continuous multi-parameter monitoring and treatment, and telemetric abilities [2, 3]. This contributes to a shift of health services from a conventional hospital-centered towards an individual-centered healthcare, which together with wireless technologies allows to a continuous feeding of relevant information back to the user and/or clinical professionals. In addition, they improve the early detection and timely response to possible health threats [2]. Since wearable, these devices are of portable nature and are sustained directly on the human body or in a part of clothing. Wearable monitoring devices sector is set to continue its rapid development throughout the years due to the added value brought to the healthcare market. According to a study made by ABI Research, the market for wearable devices will reach more than 100 million units per year, by 2016 [8].

The overall results of advances in both technological and healthcare sectors are leading to the establishment of a new paradigm – personalized health systems [2, 5]. These will enable the transfer of healthcare towards a system that will give the user a more pro-active role in its care, providing better monitoring and feedback with a comfortable and discreet solution. Likely to be a benefit to chronically ill and disabled, wearable health devices are an attractive solution for patients undergoing rehabilitation, providing them with independent living, since it allows to record and collect relevant data in the different situations of the individual's daily life [2, 3].

1.1.1 Applications

In wearable devices, a wide range of sensors is used to measure physiological and environmental conditions. The first type of sensors – physiological sensors – is used to monitor a clinical condition or process. Examples of signals measured with biomedical sensors are: heart, brain and muscle activity, blood pressure and body kinematics, among others. On the other hand, the second type of sensors – peripheral sensors – is responsible to sense the surrounding environmental conditions, enhancing the awareness of the system [3, 9]. The diversity of wearable sensors and the trends in micro and nanofabrication will eventually lead to a widespread of applications for wearable devices.

Healthcare

Failure to do a more regular health monitoring condition can lead to problematic situations, specially considering the elderly with fragile and rapidly changing health status. In addition, Medical Doctors often cannot explain how most problems develop because they usually see the patients at a late stage of illness development [10]. According to the World Health Organization (WHO), in 2008, the number of deaths due to ischemic heart disease and from stroke or another form of cerebrovascular disease was 7.3 and 6.2 million, respectively [11]. Figure 1.1 shows the ten leading causes of death in 2008.

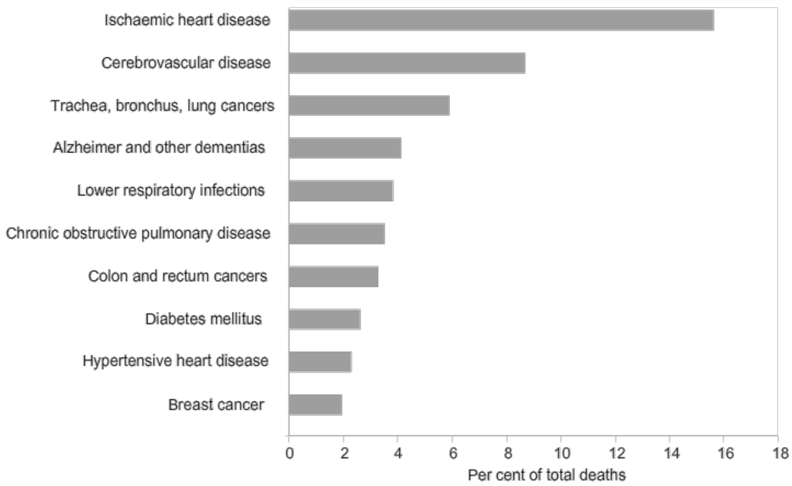

Figure 1.1 Ten leading causes of death in high-income countries in 2008 [10]. Data is taken over a sample population of 100000 inhabitants.

Regarding health conditions associated with circulatory and respiratory system, which represent the majority of deaths per year/100000 habitants (Figure 1.1), early and systematic intervention is highly valuable. The simultaneous and continuous recording of physiological signals allows to perform an intersignal elaboration and assessment of the patient's health condition status at any given time [10].

Many research groups have started to develop wearable technologies with main application in Health Science [12]. A valuable example of the importance of wearable devices in health monitoring and prevention can be found in a recent work developed by Kramer and co-workers [13]. They presented a wearable device for detecting seizures based on a three-axis accelerometer – "Motion Sensor". This device also has the ability to alert patients and families of possible seizures, as well as to assist in the preliminary recognition of these events. Preliminary tests have suggested that this sensor/alarm correctly identified 91% of the seizures with a low false alarm rate. Another important example of the applicability of wearable sensors in improving health and quality of life, is the Brain Computer Interface (BCI). Wearable and wireless BCI systems are valuable in providing augmentation of human capabilities, useful in a wide spectrum of areas from health rehabilitation to virtual reality games. Several wearable BCI systems have been proposed in the past few years. A useful review of these devices can be found in [14].

Sports, Fashion and Leisure

Sports sector, that includes a broad range of modalities, is highly demanding since most activities (individual or in team) rely on extreme physical capacities. The constant and real-time monitoring of physiological signals, functional performance and activity of athletes is therefore of extreme importance, either during training or competition. Several studies have assessed the use of wearable sensors in recognition of activity for sports and daily activity applications [15, 16]. Both studies have indicated strong feasibility of wearable sensors for activity recognition in several conditions, which is valuable for promotion of health-enhancing physical activities and sport performance assessment.

Intelligent clothing and augmented reality is one of the most important applications of wearable devices in fashion and leisure [17]. Nowadays, well-known companies such as Philips and Infineon, have come with interactive clothing based on light-emitting devices (LEDs). Lumalive is an example of this technology composed of a photonic textile with lighted graphic display medium for text and animation [18].

Industrial and Military Applications

Industrial and military fields can benefit from wearable devices since they can assist either workers or soldiers in their functions, while providing real-time feedback on health status, context awareness and others. The European project PROETEX consists in the development of wearable prototypes for addressing Civil protection envisioning urban and forest fire fighters [19]. Another example related with military applications, is the work developed by Winterhalter et al. [20], which main goal is to develop textile-based wearable devices that can be integrated into military protective clothing.

1.1.2 Design Requirements

The design of wearable systems should follow a set of requirements, especially when compared to stationary equipment due to the various operating constraints. In fact, these solutions are often used in specific conditions and need to be integrated and functional into non-controlled environments where they will operate, e.g. exercise, sleep or work. In addition and particularly in health applications, the acceptability from behalf of patients and clinicians is crucial for the successful implementation of wearable devices [21].

A recent study called “Body-Worn Sensor Design: What Do Patients and Clinicians Want?” has a valuable review of some of the most important requisites regarding patients and clinician preferences [21]. From a user point a view, the main recurring factors were: less interference with daily life activities, compact, user-friendly, embedded technology, and reduce incomings to health care facilities. All of these issues are related with the esthetics of a wearable device [22]. On the other hand, clinicians are more concerned with technical issues such as long-term and real-time monitoring, attachment of the device to the patient and storage capacity. Figure 2.1 shows the key points that need to be covered along the wearable device creative process, divided in physical, user, performance and design-related requirements [3, 2, 23, 22].

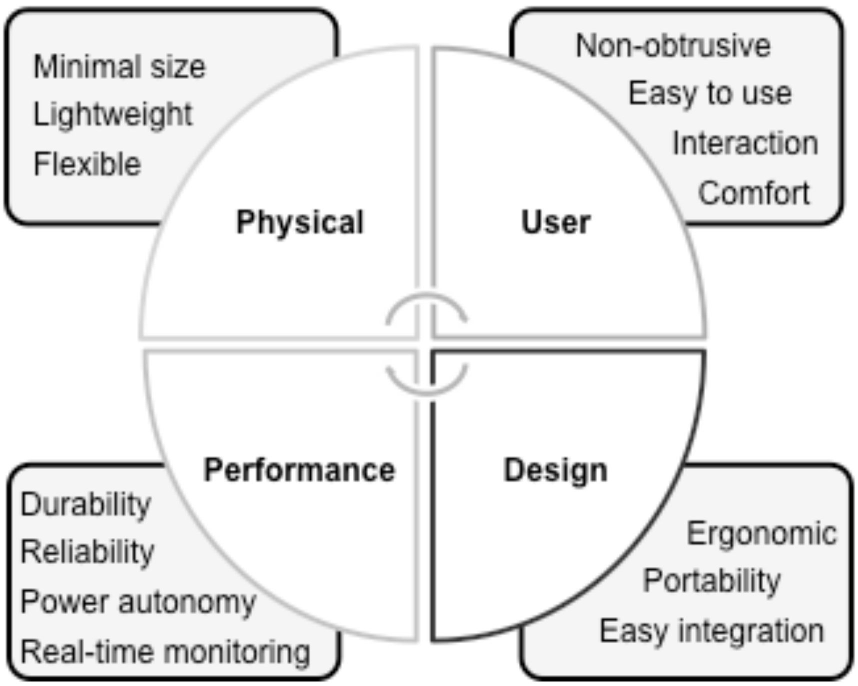

Figure 1.2 Main requirements for wearable devices acceptance by users and clinicians/technicians.

1.1.3 State of the Art

A number of wearable devices in the healthcare sector emerged in the past few years, ranging from simple monitoring of daily routine, to miniaturization and integration of sensors to enhance the overall performance of wearable systems. Wearable systems can be classified according to the level of integration of its components into the smart/functional material, i.e. substrate. There are three types of wearable systems according to this classification: 1st generation, based on attachable hardware components and sensors; 2nd generation, where these components are embedded into the material; and 3rd generation, where innovative integration techniques during the substrate material production allow for the design of multi-sensor clothing and/or accessories. Figure 1.3 presents the three generations of wearable systems, as well as some state-of-the-art for each category.

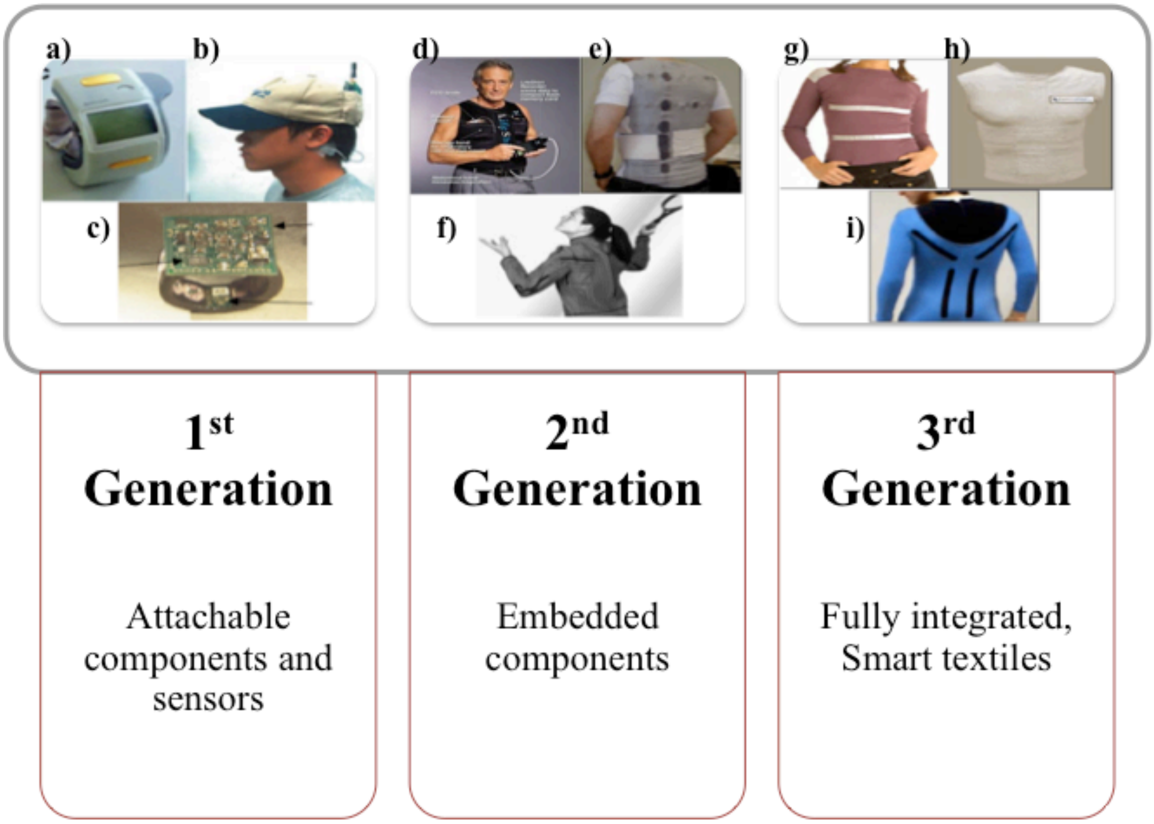

Figure 1.3 Categories of Wearable Devices and examples. Examples from the 1st generation of wearable devices from the left to the right are a a) wrist-worn device AMON [23], b) a braincap with a wireless Electroencephalography acquisition module [24] and c) a ring monitoring sensor [25]. The 2nd generation includes d) a monitoring t-shirt Lifeshirt [26], e) a sensorized T-shirt developed within the VTAM project [27] and f) a sensor jacket for context awareness [28]. The 3rd generation examples are g) a shirt developed by Smartex within the European integrated project WEALTHY [29], h) SmartShirt developed by Sensatex [21] and i) sensorized leotard developed [30].

The first wearable systems to appear were based on plug-in methods, where a supporting mechanism for attaching the necessary components is provided. These can include electrocardiogram (ECG) monitoring wristwatches, sensing components that can be attached to a t-shirt, a vest or even to a cap (Figure 1.3). The problem associated with these devices is its lack of comfort and practical solution considering the user's perspective. An example of the 1st category of wearable devices is described in the work entitled "AMON: A Wearable Medical Computer for High Risk Patients" [24]. The AMON system was developed by a European Union IST sponsored consortium and consists on a wrist worn unit with monitoring, data analysis and communication capabilities. This system is mainly intended for high-risk patients in need for constant monitoring. Choi and Jiang have developed a wearable sensor device in form of a belt-type sensor head, which is composed by conductive fabric and Polyvinylidene Fluoride (PVDF) film, for monitoring cardiorespiratory signals during sleep [25].

The drawbacks of the first generation of wearable systems leads to the design of a new generation based on partially embedded architecture, where all the necessary components are fixed to the substrate material. This not only eliminates the need for qualified personnel or for the user to place the components, running the risk of misplacement, but also allows for a more practical and discreet solution. However, there is still a considerable difference from a normal garment, meaning that the components have not a sufficient level of integration into the substrate, providing relatively comfortable solutions but yet perceptible. Lifeshirt is a product of Vivometrics, Inc. (Ventura, CA), and consists of a wearable physiological monitor in form of a chest and shoulder strap, providing non-invasive ambulatory monitoring of pulmonary cardiac function and posture [26].

The research and progress in integration techniques during the fabrication process leads to the design of a third generation of wearable health devices. This type of systems represents the front-end in wearable technology allowing to design smart, functional and multi-sensing materials that, due to the high level of integration, are apparently normal. A very popular technological example of a 3rd generation wearable system is the electronic textile – e-textile – which consists of high knowledge-content garments provided by multifunctional fabrics. Through blending of components into the user's ordinary clothing, it is possible to achieve an ideal wearable system, minimizing the hassle of wearing the device. The Georgia Institute of Technology (Atlanta) jointly with the U.S. Navy proposed one of the first wearable solutions, which consisted of a wearable vest embedded with optical fibers and sensors, working also as a data bus – the Georgia Tech Wearable Motherboard (GTWM) [27]. All the components are integrated into the fabric creating a flexible device, which was manufactured essentially for use in combat conditions. This device was placed into the market by Sensatex, Inc., as a product named SensatexSmart Shirt. The paper "Advances in textile technologies for unobtrusive monitoring of vital parameters and movements" describes the project called MyHeart that consists in functional clothes with on-body sensors and electronics to acquire, process and evaluate physiological data [28].

1.1.4 Integration

Wearable devices should consist on elegant, easy to wear and ubiquitous clothing in order to accompany the user to any place at any time. This requires the integration of sensors/actuators, power sources, processing and communication functions within the wearable material [4, 23]. First, researchers have explored the use of plug-in modules and attachable off-the-shelf electrical and optical devices and components. Nevertheless, is unsuitable for lengthy continuous monitoring due to the cumbersome modules to be carried out by the user. These limitations can be addressed with an integration of multiple smart functions into textiles or other materials.

Textiles are an ideal substrate for integrating miniaturized components since they are comfortable, pervasive and constitute the basis of almost every piece of cloth. The implementation of wearable sensors towards completely flexible devices can be performed in two major ways: the sensors can be embedded in the textile; or the fabric itself is used as a sensing structure or suite. The first approach implies the use of interconnections based on electro-active fibers, either metallic or optical, whereas the latter method consists in developing conductive yarns and fabrics with sensing capabilities [9, 29].

The use of purely electrical approaches implies the problem of local power supply and complex interconnections within the wearable suit. On the other hand, with optical fiber sensors, it's possible to design all-optic suits with attachable power supply units, in a plug-in module such as a belt. This opens the opportunity to use these devices in conditions where electrical system leans to fail, such as electromagnetic rooms (MRI rooms), or other harsh conditions [30, 31]. Many approaches to optical fibers integration have been developed, with particular interest for wearable health devices, leading to easier optical fiber integration into textiles and other wearable materials [32-36]. Since textiles are composed by a combination of multiple yarns and fibers with resemblance to optical fibers, integration of these sensors into the textile is easy and without making the final product locally thicker [30, 37]. This is possible due to the compatibility between optical and textile fibers in terms of fineness and thickness. Looking into more detail into optical fiber properties, these components have tensile strengths about 10 to 100 times larger when compared to textile fibers, resulting in more resistance to tensile load [30]. Common fabric manufacturing processes can be used to integrate optical fibers into textiles, such as weaving, knitting and spread-coating. The latter technique is one of the most promising ones since it allows to reach higher degrees of process flexibility is spread-coating which consists in producing a sandwich structure of laminates with different materials [37]. Due to it's nature of layer by layer, spread coating guarantees high-process flexibility, use of different materials and geometries, and reliable fiber positioning.

1.2 Wearable Photonic Systems

Research in photonics began between 1960s and 1970s, when lasers and light emission through optical fibers were introduced. This field is particularly profitable in applications where conventional electronic interconnections meet inherent restrictions caused by attenuation, power consumption and crosstalk. As a result, photonic sensors have become increasingly used in several fields of applications such as Healthcare, Military, Industrial or Sports. This technology-based sensors have demonstrated great capabilities as candidates for monitoring physiological and environmental changes and they offer many advantages, such as [36, 39, 44, 45]:

- Easy integration into a widespread of materials and structures;
- Resistance to harsh environments and to corrosion;
- Immunity to electromagnetic and radio frequency interference;
- Multiplexing capacity towards the design of sensing networks;
- Remote and multifunctional sensing capability;
- Electrical wire free;
- Small size and lightweight;
- Long lifetime (more than 25 years).

In addition, photonic sensors have a great economic impact considering that the global market for biophotonics is forecasted at $133 billion by 2016, with a yearly growth rate of 31% [38].

1.2.1 Bioelectric Signal Photonic Sensing

Physiological signals include bioelectric events and other biochemical and physical parameters that are crucial for assessment of the user's health status. In particular, bioelectric signals represent the electrical activity related to the physiology and function of organs and systems, such as heart, brain and muscles [22, 23].

Bioelectric signals can be detected in suitable sites on the surface of the body, since the electric field propagates through the biological medium. Therefore, this allows for a non-invasive acquisition of such signals providing vital clues as to normal functions of organs. This leads to useful and reliable means of health condition monitoring. For example, Electroencephalograms (EEG), a bioelectric signal originated by brain activity, can help to identify epileptic seizure events [13, 39].

Not every sensor can be used in a wearable context, specially looking at the user's perspective. It has to be taken into account not only its physical attributes such as size and weight, but also its non-invasive character and easy placement. In addition, these sensors must ideally produce an electrical output in order to be digitally processed, being durable, reliable and low-power consumption [3, 40].

Photonic sensors fulfill the above requirements with the added value of eliminating the use of electrical connections in the piece of cloth or accessories. When dealing with photonic sensors, the following main function blocks are needed to correctly perform bioelectric sensing: optical signal generation, light modulation and photodetection. Figure 1.4 shows the typical acquisition system of an optical sensor.

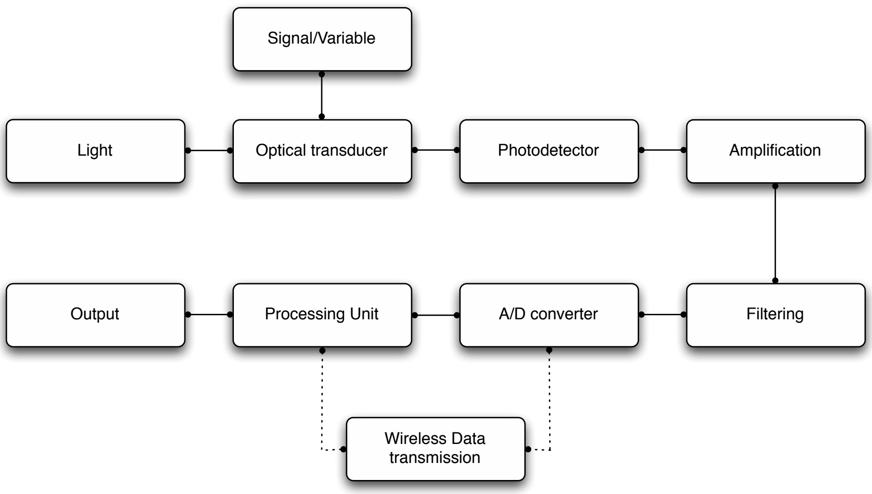

Figure 1.4 Optical sensor acquisition block diagram.

Photonic acquisition systems must include a light source that will pass through an optical transducer, i.e. optical modulator. In the presence of a particular signal, the optical transducer will produce a shift in light properties, whether if it's intensity, phase, polarization or other. Afterwards, a photodetector is responsible to collect this modulated light, converting this optical modification into a electrical entity. The latter is dependent on the type of photodetection circuitry applied in this stage, where a photodiode can be used in order to convert light intensity into current or voltage. The analog signal obtained is converted to digital forms by A/D converters and further processed using different algorithms. If necessary the processed signals can be converted back to analog forms to drive specific devices. Some applications, it's often necessary to include wireless communication systems that enable the sensing component to transmit the data to a control-processing unit or even to a database service.

1.2.2 EO Sensing Methodologies

Electro-optic (EO) sensors use specific transducer effects by which an optical signal or material exhibits a particular response in the presence of an external electric field. The materials exhibiting this type of stimulus-response mechanism are classified as EO materials. Some of these materials are included in Table 1.1. The EO component works as the sensing element, which can be in form of a coating material, such as a hydrogel or a piezoelectric material, or even used as a device like an EO intensity modulator. Several effects or materials can be used as the EO sensing component, and they can be divided into different categories, each of one with a specific associated effect. Table 1.1 shows some of the different effects that can be applied in the sensing mechanism of a photonic wearable device, as well as examples of materials and signals detected.

Table 1.1 Different EO transducer effects applied in the sensing mechanism for wearable devices [29, 41-43].

<table>
<tr><th>Transducer Effect</th><th>Sensing devices</th><th>Stimulus</th><th>Response</th><th>Examples of Materials</th><th>Bioelectric signal</th></tr>
<tr><td>Electro-optic</td><td>EO modulators</td><td>Electric field</td><td>Birefringence</td><td>Lithium Niobate ($LiNbO_3$), Lithium tantalite ($LiTaO_3$), EO polymers</td><td>EEG, ECG, EMG, EOG</td></tr>
<tr><td>Electroluminescence</td><td>Light Emission Devices</td><td>Electric field</td><td>Light emission</td><td rowspan="2">Electroactive Polymers (EAPs)</td><td>ECG, EMG</td></tr>
<tr><td>Photoluminescence</td><td>Photoluminescense sensors Example: UV radiation sensor</td><td>Incident light</td><td>Light emission</td><td>UV radiation</td></tr>
</table>

Since the stimulus for EO operation relies on an external electric field, an important feature of photonic sensors is the ability to more easily enable contactless measurements of physiological events, particularly electrophysiological signals.

1.2.3 Bioelectroptic Sensing – State of the Art

A few studies have explored the use of EO sensors in wearable monitoring bioelectric activity [44, 45]. In particular, Kingsley and co-workers, have developed an EO sensor based on intensity modulation called Photrodes™. This sensor is specially envisioned for EEG and ECG monitoring of Army soldiers [46]. Despite proper operation, these works are not a complete photonic bioelectric sensing platform.

1.3 Motivation and Objective

Current healthcare systems are facing a fundamental transformation mainly driven by the growing aging population, increasing healthcare costs, reduced quality of life and prevalence of chronic diseases. People are acquiring more health consciousness and are prone to assume a more active role in managing their own health and life style [6].

The development of miniature and portable sensors that can be used unobtrusively or can be part of clothing items, i.e., wearable sensors, have opened countless solutions to deliver healthcare beyond the hospital context, in the home or during outdoor daily activities. These systems enhance the quality of life of patients in rehabilitation, chronically ill or disabled, while being financially rewarding by reducing hospitalization. In fact, this can be achieved either through prevention of disease progress or by providing suitable resources for independent living [3].

Regardless of other physiological signals, bioelectric monitoring is of extreme importance, since it provides information on the activity of organs such as heart, brain, and muscles. Such information is required not only when assessing and monitoring patient's health status, but also valuable under non-clinical scenarios, such as for monitoring professional workers, particularly when in contact with stressful conditions. Therefore, the development of sensing interfaces designed to non-invasively obtain the ECG, EMG and EEG is demanded.

Despite the ability to monitor the low-amplitude high-impedance bioelectric signals sources, available technologies have not yet solved the drawbacks associated with embedding sensors and electronic components into clothing items. The most advanced wearable solutions are based on conductive fabrics that use conductive fibers or yarns, serving as interconnects and sensors [29, 37]. Nevertheless, since using electrical interconnections, such technologies are highly susceptible to electromagnetic interferences and movement artifacts. Moreover, such solutions require the use of probe currents or voltages that may raise safety concerns.

Photonic technologies contribute to the development of sensing solutions when electrical counterparts fail due to problems associated with power consumption, power loss, or electromagnetic interference. Features such as miniaturization, flexibility, multiplexing capabilities and the fact that transmission losses of optical signals are considerably reduced, underscore their great promise. Photonic sensors show compact design and high level of integration into several materials, whereas the problem with interconnections and electronics is considerably reduced [32-36]. The embedment of photonic sensing elements into clothing items makes possible to achieve long-term monitoring of multi-parameter, while being easily customized according to the needs of each individual system, promoting the comfort when wearing such systems. In fact, recent integration technologies have proven to be feasible for optical fiber integration into polymeric materials [34]. Recent studies have also explored optical-based sensors for bioelectric activity recording [44, 45] but, despite the obtained good results, a full solution to acquire the main bioelectric signals, i.e. ECG, EMG and EEG is still lacking.

The main achievement of this thesis was the design and characterization of a multi-bioelectric signal acquisition platform, based on photonic technologies, suitable for further use in wearable applications. The system investigated in this thesis is based on electro-optic (EO) methods, consisting in a Lithium Niobate ($LiNbO_3$) Mach-Zehnder Interferometer (MZI) modulator, and optoelectronic (OE) circuitry for signal translation, filtering and amplification (Figure 1.5). The designed platform allows for multiple bioelectric signals to be extracted and recorded from several locations, and the front-end acquisition is only composed by optical fibers as interconnections. The main goal is to provide a photonic platform compatible with integrated and miniaturized components towards the design of wearable monitoring garment. This garment could include, for instance, a wearable brain cap for EEG monitoring and a t-shirt or vest for ECG and EMG monitoring.

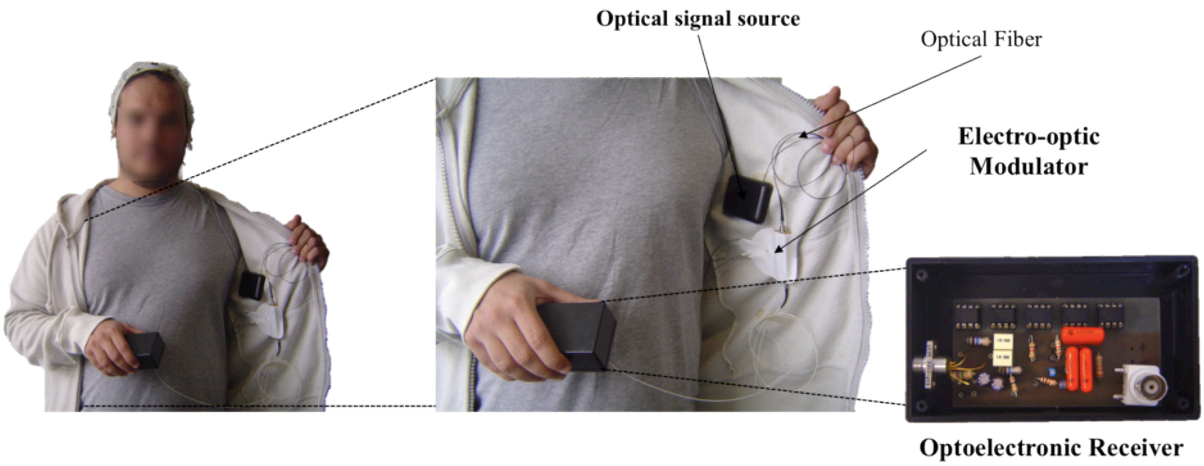

Figure 1.5 Photonic platform for bioelectric signal acquisition on wearable devices, developed in this thesis.

1.4 Thesis Organization

This chapter introduced the subject of wearable devices in healthcare and presented the thesis's motivation as well as the objectives. Chapter 2 describes the bioelectric signal acquisition theory, including its signal properties as well as typical acquisition components. Chapter 3 focuses on the photonic bioelectric signal sensor, particularly in the phenomena behind the sensor mechanism and the selected components. Technology selection is explored and analyzed in terms of performance and modeled in order to determine the bottleneck of the photonic system. Chapter 4 deals with the OE system design that supports the EO conversion performed during bioelectric signal acquisition. The performance of the OE system is analyzed following Chapter 3 system overview. Chapter 5 presents the developed prototyped for testing photonic bioelectric signal acquisition and results. These results consisted in first analyze overall photonic platform bioelectric acquisition in terms of sensitivity, process linearity throughout EO and OE stages. Additionally, the developed photonic platform is compared with standard bioelectric acquisition setups using human subjects. Finally, Chapter 6 draws the main conclusions as well as a few recommendations for future work.

References

[1] WHO, "http://www.who.int/gho/health_financing/en/index.html," 2011.

[2] X.-F. Teng, Y.-T. Zhang, C. C. Y. Poon, and P. Bonato, "Wearable Medical Systems for p-Health," *Biomedical Engineering, IEEE Reviews in*, vol. 1, pp. 62-74, 2008.

[3] D. I. Fotiadis, C. Glaros, and A. Likas, "Wearable Medical Devices," in *Wiley Encyclopedia of Biomedical Engineering*, John Wiley & Sons, Inc., 2006.

[4] P. Lukowicz, T. Kirstein, and G. Tröster, "Wearable systems for health care applications.," *Methods of information in medicine*, vol. 43, no. 3, pp. 232-8, Jan. 2004.

[5] S. Park and S. Jayaraman, "Enhancing the quality of life through wearable technology.," *IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society*, vol. 22, no. 3, pp. 41-8, 2003.

[6] A. Lymberis, "Intelligent biomedical clothing for personal health and disease management: state of the art and future vision," *Telemedicine Journal and e-health*, vol. 9, no. 4, 2003.

[7] J. E. Bardram, "Pervasive Healthcare as a Scientific Discipline," *Methods of Information in Medicine*, pp. 178-185, 2008.

[8] A. Bonfiglio, *Wearable Monitoring Systems*. Springer Verlag, 2010.

[9] P. Bonato, "Clinical applications of wearable technology.," *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2009, pp. 6580-3, Jan. 2009.

[10] WHO, "http://www.who.int/whosis/whostat/2011/en/index.html," 2011. [Online]. Available: http://www.who.int/whosis/whostat/en/index.html.

[11] A. Pantelopoulos and N. G. Bourbakis, "A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 40, no. 1, pp. 1-12, Jan. 2010.

[12] U. Kramer, S. Kipervasser, A. Shlitner, and R. Kuzniecky, "A Novel Portable Seizure Detection Alarm System: Preliminary Results," *Journal of Clinical Neurophysiology*, vol. 28, no. 1, p. 36, 2011.

[13] C.T. Lin et al., "Review of wireless and wearable electroencephalogram systems and brain-computer interfaces--a mini-review.," *Gerontology*, vol. 56, no. 1, pp. 112-9, Jan. 2010.

[14] M. Ermes, J. Pärkka, J. Mantyjarvi, and I. Korhonen, "Detection of daily activities and sports with wearable sensors in controlled and uncontrolled conditions.," *IEEE transactions on information technology in biomedicine : a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 12, no. 1, pp. 20-6, Jan. 2008.

[15] J. Pärkkä, M. Ermes, P. Korpipää, J. Mäntyjärvi, J. Peltola, and I. Korhonen, *Activity classification using realistic data from wearable sensors.*, vol. 10, no. 1. Piscataway, NJ: IEEE, c1997-, 2006, pp. 119-128.

[16] T. Starner, S. Mann, B. Rhodes, and J. Levine, "Augmented reality through wearable computing," *Presence:*, 1997.

[17] Philips, "Philips Lumalive fabrics – creating a magic lighting experience with textiles "," *World*, no. 28, 2006.

[18] D. Curone et al., "Smart garments for safety improvement of emergency/disaster operators.," *Conference Proceedings of the International Conference of IEEE Engineering in Medicine and Biology Society*, vol. 2007, pp. 3962-3965, 2007.

[19] C. A. Winterhalter et al., "Development of electronic textiles to support networks, communications, and medical applications in future U.S. military protective clothing systems.," *IEEE transactions on information technology in biomedicine a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 9, no. 3. pp. 402-406, 2005.

[20] J. H. M. Bergmann and a H. McGregor, "Body-worn sensor design: what do patients and clinicians want?," *Annals of biomedical engineering*, vol. 39, no. 9, pp. 2299-312, Sep. 2011.

[21] F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer, and R. Martin, "Design for wearability," *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*, pp. 116-122.

[22] S. Park and S. Jayaraman, "Smart textiles: Wearable electronic systems," *MRS bulletin*, vol. 28, no. 8, pp. 585–591, 2003.

[23] U. Anliker et al., "AMON: a wearable multiparameter medical monitoring and alert system," *Ieee Transactions On Information Technology In Biomedicine*, vol. 8, no. 4, pp. 415-427, 2004.

[24] S. Choi and Z. Jiang, "A novel wearable sensor device with conductive fabric and PVDF film for monitoring cardiorespiratory signals," *Sensors and Actuators A: Physical*, vol. 128, no. 2, pp. 317-326, Apr. 2006.

[25] P. Grossman, "The LifeShirt: a multi-function ambulatory system monitoring health, disease, and medical intervention in the real world.," *Studies In Health Technology And Informatics*, vol. 108, pp. 133-141, 2004.

[26] C. Gopalsamy, S. Park, R. Rajamanickam, and S. Jayaraman, "The Wearable MotherboardTM : The First Generation Responsive Textile Structures Medical Applications," *Virtual Reality*, pp. 152-168, 1999.

[27] R. Paradiso and D. De Rossi, "Advances in textile technologies for unobtrusive monitoring of vital parameters and movements.," *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 1, pp. 392-5, Jan. 2006.

[28] F. Carpi and D. De Rossi, "Electroactive polymer-based devices for e-textiles in biomedicine," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 9, no. 3, pp. 295–318, 2005.

[29] J. Rantala, J. Hännikäinen, and J. Vanhala, "Fiber optic sensors for wearable applications," *Personal and Ubiquitous Computing*, vol. 15, no. 1, pp. 85-96, Jun. 2010.

[30] J. Hesse and W. Sohler, "Fiber optic sensors," *Oceans 82*, no. 1, pp. 257-259, 1984.

[31] F. Berghmans et al., "Photonic Skins for Optical Sensing Highlights of the PHOSFOS Project," *20th International Conference on Optical Fibre Sensors, Proceedings of the SPIE, vol. 7503, pp. 75030B-75030B-*, vol. 4, 2009.

[32] M. a El-Sherif, J. Yuan, and A. Macdiarmid, "Fiber Optic Sensors and Smart Fabrics," *Journal of Intelligent Material Systems and Structures*, vol. 11, no. 5, pp. 407-414, May. 2000.

[33] A. Ferreira et al., "A Smart Skin PVC Foil Based on FBG Sensors for Monitoring Strain and Temperature," no. c, 2010.

[34] E. Bosman et al., "Fully Flexible Optoelectronic Foil," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, no. 5, pp. 1355-1362, Sep. 2010.

[35] E. Bosman, G. Van Steenberge, P. Geerinck, J. Vanfleteren, and P. Van Daele, "Fully embedded optical and electrical interconnections in flexible foils," in *Microelectronics and Packaging Conference, 2009. EMPC 2009. European*, 2009, pp. 1–5.

[36] X. Tao and T. Institute, *Wearable electronics and photonics*. Crc Press, 2005.

[37] "Biophotonics Market Predicted to Hit $133 Billion by 2016." [Online]. Available: http://www.photonics.com/Article.aspx?AID=27453.

[38] N. Verma, A. Shoeb, J. Bohorquez, J. Dawson, J. Guttag, and A. P. Chandrakasan, "A Micro-Power EEG Acquisition SoC With Integrated Feature Extraction Processor for a Chronic Seizure Detection System," *IEEE Journal of Solid-State Circuits*, vol. 45, no. 4, pp. 804-816, Apr. 2010.

[39] J. M. Winters, Y. Wang, and J. M. Winters, "Wearable sensors and telerehabilitation.," *IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society*, vol. 22, no. 3, pp. 56-65, 2003.

[40] G. K. Knopf and A. S. Bassi, *Smart biosensor technology*. CRC Press, 2007, p. 636.

[41] R. Lane and B. Craig, "Materials that sense and respond – An introduction to smart materials," *Structure*, vol. 7, no. 2, pp. 9-14.

[42] J. Luprano, J. Sola, A. Ridolfi, S. Pasche, and B. Gros, "New generation of smart sensors for biochemical and bioelectrical applications," *Strain*, 2007.

[43] S. a Kingsley, "Photrodes for physiological sensing," *Proceedings of SPIE*, pp. 158-166, 2004.

[44] A. Sasaki, A. Furuya, and M. Shinagawa, "Study of semiconductor electro-optic modulators for sensing extremely-low-frequency electrical signals," *Sensors and Actuators A: Physical*, vol. 151, no. 1, pp. 1-8, Apr. 2009.

[45] S. A. Kingsley, "Revolutionary optical sensor for physiological monitoring in the battlefield," *Proceedings of SPIE*, vol. 5403, pp. 68-77, 2004.