32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

Low Power Wireless Acquisition Module for Wearable Health Monitoring Systems

C.P. Figueiredo, *Student Member, IEEE*, K. Becher, *Member, IEEE*, K.-P. Hoffmann, *Member, IEEE,* P.M. Mendes, *Member, IEEE*

Abstract— **This paper presents a low power wireless acquisition module for use within wearable health monitoring systems and Ambient Assisted Living applications. The acquisition module provides continuous monitoring of the user's electrocardiogram (ECG) and activity, as well as the local temperature at the module. The module is placed on the chest of the user, and its wearability is achieved due to its fabrication based on a flexible PCB, and by the complete absence of connecting wires, as a result of the integration of flexible and dry ECG monitoring electrodes on the acquisition module, which do not require preparation with electrolyte gel. The design of the acquisition module also aimed for the minimization of power consumption to enable long-term continuous monitoring, namely concerning the wireless link, for which a proprietary low power solution was adopted. A low power analog frontend was custom designed for single-lead ECG monitoring, achieving a current consumption of 220 µA. The wireless acquisition module has a current consumption down to 1.3 mA while processing the acquisition of sensor data, and 4 mA when the wireless transceiver is active.**

Keywords: Low Power, Wireless Sensing Methods, Body Sensor Networks and Telemetric Systems, Wearable Health Monitoring.

I. INTRODUCTION

HEALTHCARE services and resources are currently being confronted with an ever-increasing demand. This tendency is mainly being driven by the unprecedented ageing of the world population, and the consequent increase in the incidence of chronic disease and physical disability, which is causing global healthcare costs to rise [1]. These problems are stimulating the research community to develop innovative solutions on Ambient Assisted Living [2] and Wearable Health Monitoring Systems (WHMS) [3], with the goal of providing caregivers with alternative and more efficient methods for close observation and monitoring of the health condition of a patient, outside of the hospital environment.

WHMS are nowadays regarded as a promising emerging field, combining different technologies such as sensors, communications, information and materials, having the potential to increase the quality and efficiency of healthcare [4], and to promote a shift in healthcare systems towards proactive and preventive wellness management instead of reactive disease management [5]. In fact, the development and dissemination of these devices in healthcare systems is profitable to both patients and caregivers. Concerning patients, WHMS can contribute to increase their quality of life and independence, and to promote healthier lifestyles. Wearable systems allow patients to stay active and to keep their lifestyles, while having their health condition being monitored in their own familiar environment, thus avoiding the need for hospitalization and associated inconvenience to the patient. For caregivers, WHMS provide new means for patient observation, allowing their health condition to be both continuously and remotely monitored. Continuous health monitoring facilitates the detection of symptoms and signs of disease at an early stage, which influences the medical decisions on treatment and its effectiveness, preventing the development of severe health complications. This is particularly suitable for the treatment of patients at risk, such as those with chronic diseases or undergoing rehabilitation [6]. Hence, continuous health monitoring contributes to more effective use of the limited healthcare resources and to the reduction of global costs involved with healthcare [7-8].

Regardless of their potential, the dissemination of WHMS on healthcare systems and their acceptance by caregivers and patients may be held back if their design fails to satisfy user and application requirements. Among these requirements are:

Unobtrusiveness: patients must feel comfortable when using WHMS and, ideally, their use should not cause any restrictions to the user's activity. Also, patients may feel stigmatized to use WHMS if they are easily noticed to others [9]. As such, WHMS should feature small dimensions, light-weight and noninvasiveness.

Wireless communication: wireless technology contributes to enhance patient mobility and comfort by removing lead connections between the monitoring system and the display or storage system, and also to enable continuous monitoring of the health condition of the patient on a remote system.

Low power consumption: WHMS are typically battery powered, and their recharge implies their temporary removal

Manuscript received June 23, 2010.

This work was supported by the Portuguese Foundation for Science and Technology under grant SFRH/BD/40341/2007 and project PTDC/EEA-TEL/65286/2006.

C.P. Figueiredo and P.M. Mendes are with the Algoritmi Research Center, University of Minho, Guimarães, Portugal (emails: {celso.figueiredo, paulo.mendes}@dei.uminho.pt).

C.P. Figueiredo, K. Becher and K.-P. Hoffmann are with the Fraunhofer Institute for Biomedical Engineering (IBMT), Medical Engineering and Neuroprosthetics Dept., St. Ingbert, Germany (emails: {celso.figueiredo, kai.becher, klaus.hoffmann}@ibmt.fraunhofer.de).

and interruption of health monitoring. High capacity batteries are typically bulky and therefore unsuitable for WHMS. Hence, to maximize the uptime of WHMS and enable long health monitoring periods (e.g. few days up to a week), their operation time should be optimized based on a tradeoff between power consumption and battery capacity.

User-friendliness: as the users of WHMS may not be technically skilled, their operation should as autonomous as possible and easy to perform by the user. The maintenance of the WHMS should also be simple to perform (placement, removal and recharging).

In this work, a low power wireless acquisition module was built to be used with WHMS. The acquisition module features continuous monitoring of single-lead electrocardiogram (ECG), temperature and activity, and its design takes the aforementioned requirements into account, namely low power consumption.

II. Wearable Health Monitoring System Overview

The currently presented wireless acquisition module was developed to be used as a component of a WHMS, and it is placed at the patient's chest with the help of a chest strap or stretchy textile. Fig. 1 illustrates the use of the presented wireless acquisition module in a WHMS.

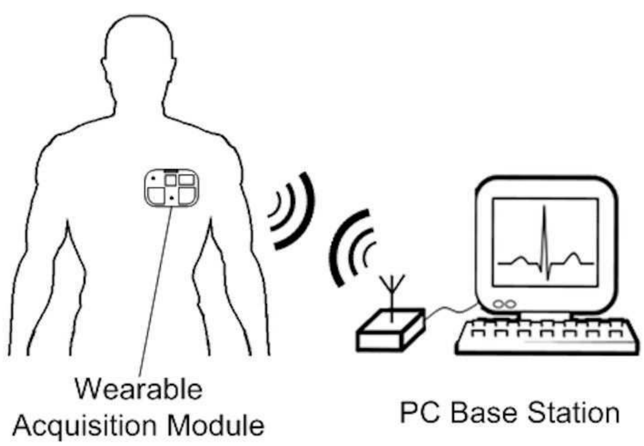

Fig. 1. WHMS featuring the presented low power wireless acquisition module.

The wearability of the acquisition module is made possible due to its assembly on a small-sized flexible printed circuit board (PCB), which allows adaptation to different chest morphologies. Moreover, flexible dry electrodes for ECG monitoring are used [10], with comparable performance to conventional Ag/AgCl electrodes, and are directly attached to the bottom side of the acquisition module's PCB, avoiding the need for skin preparation with electrolyte gel and irritation of the patient's skin on long monitoring periods. This feature, combined with the use of wireless communication, allows for the complete absence of connecting wires between the different components of the WHMS, in an attempt to reach improved comfort and freedom of movement of the monitored patient.

The wireless acquisition module is able to continuously sample single-lead ECG and activity signals from the monitored subject, along with the local temperature at the module, and to transmit these signals to a nearby base station, connected to a personal computer for signal display or further processing. The wireless acquisition module and its architecture are described in more detail in the next section.

III. Low Power Wireless Acquisition Module

The low power wireless acquisition module contains sensors for monitoring different signals related to the health condition and activity of the patient, connected to a low power microcontroller and transceiver unit. It is assembled as a flexible 4-layer PCB, whose bottom layer contains flexible dry electrodes and contacts the chest of the patient, whereas the top layer houses all of the remaining electronic components for sensing, processing and wireless communication. The architecture of the developed low power wireless acquisition module is summarized on Fig. 2.

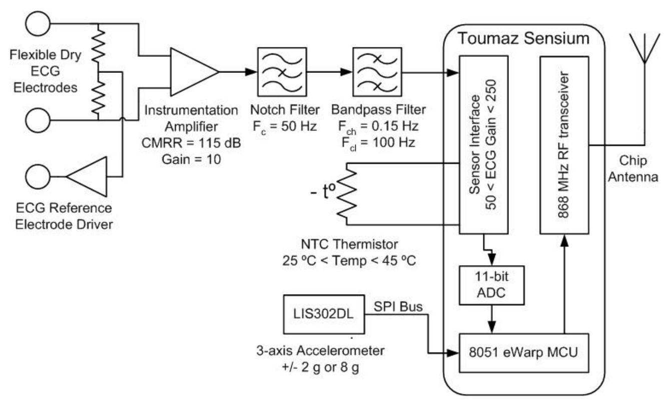

Fig. 2. Architecture of the presented low power acquisition module for WHMS.

The first prototype of the wireless acquisition module was

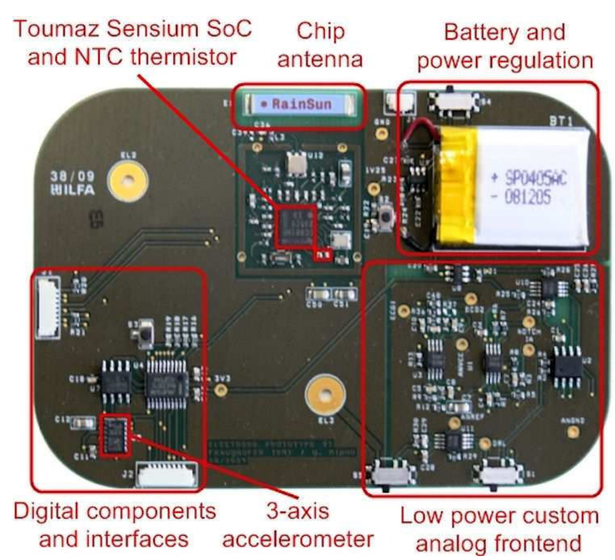

Fig. 3. Top view of the wireless acquisition module PCB.

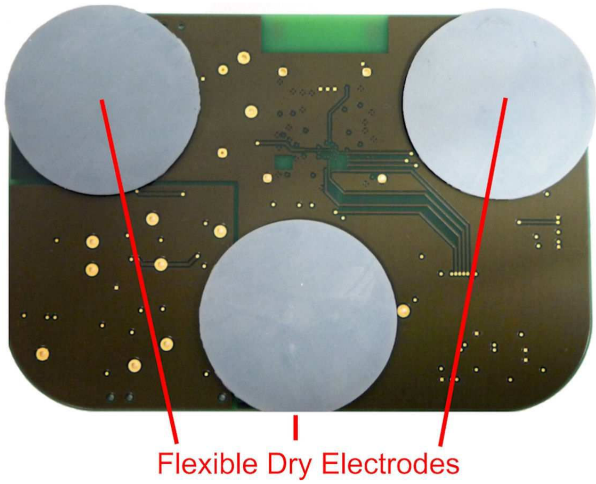

Fig. 4. Bottom view of the wireless acquisition module PCB.

developed to achieve low power consumption, and it is shown in Fig. 3 and Fig. 4.

A. Wireless Link

The Toumaz Sensium System-on-Chip (SoC) [11-12] was selected to provide the processing and wireless communication capabilities of the acquisition module, attending to its low power consumption design goal, as the Toumaz Sensium currently represents state-of-the-art in terms of low power consumption [1]. The Toumaz Sensium SoC comprises a reconfigurable sensor interface, an 8051 eWarp microcontroller unit, an 11-bit ADC and a RF transceiver. The provided wireless link between the acquisition module and the PC base station follows a proprietary energy-efficient MAC protocol, operating at the 868 MHz ISM band, at a data rate of 50 kbps. The adoption of a proprietary solution, operating at 868 MHz, is also useful to avoid the overly crowded 2.4 GHz band [13], thus improving the resilience to interference from other wireless networks infrastructures and its quality of service. If required, up to 8 wireless acquisition modules can communicate with a single PC base station, forming a star-shaped wireless sensor network [12].

B. Single-lead ECG Monitoring

The single-lead ECG signal is measured between a pair of surface electrodes, which are both flexible and dry [10], and hence suitable for integration with a WHMS. A third electrode is used as a reference driver for improvement of the common mode rejection ratio (CMRR) of the monitored ECG signal. The three electrodes are directly attached to the bottom layer of the PCB of the acquisition module (refer to Fig. 4), avoiding uncomfortable loose lead wires, which can also couple electromagnetic interference.

A low power analog frontend was custom designed to amplify and filter the single-lead ECG signal provided by the flexible dry electrodes. Its design is based on a trade-off between high CMRR and low power consumption. The first stage of the analog frontend (refer to Fig. 2) uses the MAX4194 instrumentation amplifier (Maxim Integrated Products), as it features typical CMRR and current consumption of 115 dB and 93 µA, respectively. A notch filter, centered at 50 Hz, is used in the second stage, to attenuate the 50 Hz interference pickup from surrounding mains power, since the acquired ECG signal is very low in amplitude and could be superimposed by interfering signals, depending on the environment in which the acquisition module is required to operate. The third and last stage consists of a band-pass filter, which limits the bandwidth of the monitored ECG signal to between 0.15 and 100 Hz. The notch and band-pass filters, as well as the reference electrode driver are assembled using the OPA2369 operational amplifier (Texas Instruments), which has typical CMRR and current consumption values of 114 dB and 700 nA per channel. The resulting signal from the analog frontend is then connected to the Toumaz Sensium, which adds further gain to the signal (between 50 and 250) and converts the signal to a 11-bit digital format at a rate of 250 samples/second.

C. Activity and Temperature Monitoring

The activity of the patient is monitored using a LIS302DL digital output accelerometer (STMicroelectronics), which is connected to the Toumaz Sensium via Serial Peripheral Interface (SPI) bus. This accelerometer senses 3-axis motion between ranges of ± 2 g or ± 8 g, with a current consumption of about 300 µA. The accelerometer data can be used to classify or profile the activities of the patient or for fall detection.

The local temperature at the acquisition module is evaluated from the variation in resistance of a negative temperature coefficient thermistor. Temperature can be evaluated in the range of between 25 and 45º C. Information on the local temperature of the module can be useful when monitoring, e.g., a firefighter or an athlete.

IV. RESULTS

A. Single-lead ECG Monitoring

Fig. 5 shows a 10 second period of a single-lead ECG signal, obtained when placing the wireless acquisition module slightly below the sternal region of the chest.

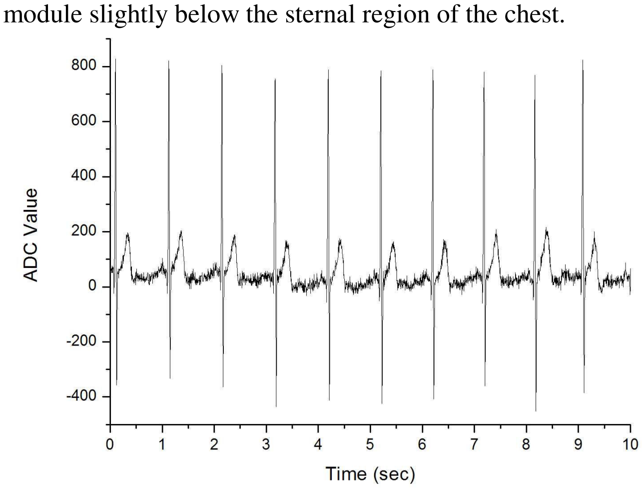

Fig. 5. Obtained single-lead ECG signal from the wireless acquisition module.

It can be seen from Fig. 5 that the obtained ECG signal has suitable quality for accurate detection of different features of the ECG waveform such as the QRS complex and the T wave, as well as elevation of the ST segment and the RR and QT intervals. Therefore, the ECG signal obtained from the wireless acquisition module is suitable for accurate heart calculation and for the detection of arrhythmia conditions.

B. *Activity Monitoring*

On Fig. 6, the result of a test is shown, in which the accelerometer data is monitored from a user wearing the wireless acquisition module. The user is walking back and forth until about 15 seconds, and then starts running in the same fashion. The X-axis or the accelerometer is vertically oriented, whereas the Y-axis and the Z-axis are horizontally oriented and perpendicular to each other, with the latter being oriented in the direction the user is moving.

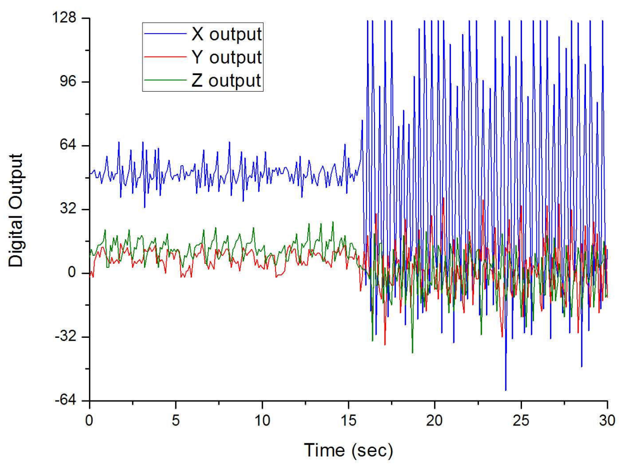

Fig. 6. Obtained activity from the 3-axis accelerometer included in the wireless acquisition module, showing the difference between walking (until 15 seconds) and running (from 15 seconds to 30 seconds).

C. *Current Consumption*

The current consumption of the wireless acquisition module was measured in different operating modes, and setting different clock frequencies to the microcontroller unit (MCU). Current consumption was measured while the MCU is processing signal acquisition (MCU on, Transceiver off) and when the monitored data is transmitted to the base station, requiring both the MCU and the wireless transceiver to be active (MCU on, Transceiver on). The current consumption of the developed ECG analog frontend was also measured. The measured values are shown in Table I.

The obtained current consumption values are in accordance with the goal of low power consumption and long operation time. The acquisition module is able to operate continuously for a period of more than 90 hours, when powered by a small rechargeable lithium-ion battery with capacity of 150 mAh.

TABLE I
MEASURED CURRENT CONSUMPTION VALUES

Operating Mode	MCU Clock Frequency			
	16 MHz	8 MHz	4 MHz	1 MHz
MCU on Transceiver off	3.5 mA	2.4 mA	1.8 mA	1.4 mA
MCU on Transceiver on	6.2 mA	5.1 mA	4.6 mA	4.2 mA
Analog Frontend	220 μA			

V. CONCLUSION

A wireless low power acquisition module is presented for monitoring of ECG and activity of patients, along with the local temperature of the module, within a wearable health monitoring system. The wearability and long-term operation of the acquisition module is supported by its wireless communication capability, fabrication on a flexible PCB, absence of connecting lead wires due to the attachment of flexible dry electrodes and by its low power consumption.

Future work will involve the reduction of the dimensions of the acquisition module, the enhancement of the quality of the monitored signals and further evaluation of system performance, particularly when multiple acquisition modules are used in the same network.

REFERENCES

[1] Y. Hao and R. Foster, "Wireless body sensor networks for health-monitoring applications," *Physiol. Meas.*, vol. 29, pp. R27-R56, Nov. 2008.

[2] Ambient Assisted Living Joint Program [Online]. Available: www.aal-europe.org

[3] A. Pantepoulos and N.G. Bourbakis, "A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis," *IEEE Trans. Syst., Man, Cybern. – Part C: Appl. Rev.,* vol. 40, no. 1, pp. 1-12, Jan. 2010.

[4] A. Lymberis, "Smart Wearable Systems for Personalized Health Management: Current R&D and Future Challenges," in *Proc. 25th Ann. Int.Conf. IEEE EMBS*, 2003, pp. 3716-3719.

[5] A. Milenković, C. Otto and E. Jovanov, "Wireless sensor networks for personal health monitoring: Issues and an implementation," *Computer Communications*, vol.29, pp.2521-2533, Aug. 2006.

[6] F. Axisa *et al.*, "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," *IEEE Trans. Inf. Biomed.*, vol. 9, no. 3, Sep. 2005.

[7] U. Varshney, *Pervasive Healthcare Computing: EMR/HER, Wireless and Health Monitoring*, New York: Springer Science + Business Media, LLC, 2009, ch. 5.

[8] I. Neild, D.J.T. Heatley, R.S. Kalawsky and P.A. Bowmann, "Sensor Networks for Continuous Health Monitoring," *BT Tech. Journal*, vol. 22, no. 3, Jul. 2004.

[9] R. Fensli and E. Boisen, "Human Factors Affecting the Patient's Acceptance of Wireless Biomedical Sensors," in BIOSTEC 2008, CCIS 25, A. Fred, J. Filipe and H. Gamboa, Eds. Berlin Heidelberg: Springer-Verlag, 2008, pp. 402-412.

[10] K.-P. Hoffmann and R. Ruff, "Flexible dry surface-electrodes for ECG long-term monitoring," in *Proc. 29th Annu. Int. Conf. IEEE EMBS*, 2007, pp. 5739-5742.

[11] A. Wong *et al.*, "A 1V Wireless Transceiver for an Ultra-Low-Power SoC for Biotelemetry Applications," *IEEE J. Solid-State Circuits*, vol. 43, no. 7, pp. 1511:1521, Jul. 2008.

[12] Toumaz Technology Limited [Online] Available: www.toumaz.com

[13] G. Zhou, J.A. Stankovic and S.H. Son, "Crowded Spectrum in Wireless Sensor Networks," in *Proc. EmNets 2006*.