TOWARDS WEARABLE AND CONTINUOUS 12-LEAD ELECTROCARDIOGRAM MONITORING

Synthesis of the 12-lead Electrocardiogram using 3 Wireless Single-lead Sensors

C. P. Figueiredo and P. M. Mendes

Centro Algoritmi, University of Minho, Dep. Industial Electronics, Campus Azurém, 4800- 058 Guimarães, Portugal

Keywords: Health Monitoring Devices, Biotelemetry, Wireless Systems, Wearable Systems, 12-lead ECG Synthesis, 12-lead ECG Reconstruction, Low-Power Design.

Abstract: Wearable health monitoring systems have emerged in the last decade as innovative means for patient observation and healthcare delivery. Among the physiological signals which can be measured using such systems, the 12-lead electrocardiogram is arguably the most important. However, continuous monitoring of the standard 12 lead electrocardiogram is impractical and unattractive for a wearable system, due to the obtrusiveness and discomfort that the placement and connection of 10 electrodes would cause. In this regard, the use of reduced lead sets for the synthesis of the 12-lead electrocardiogram is a preferable solution. This work analyses the suitability of a wireless sensor network prototype for continuous and simultaneous monitoring of a set of 3 modified electrocardiogram leads, which can be used for synthesis of the 12-lead electrocardiogram by application of a patient-specific transformation matrix, estimated by multiple linear regression.

1 INTRODUCTION

The development of wearable systems for health monitoring has, since the last decade, been an active research topic with growing attention (Pantepoulos and Bourbakis, 2010), benefiting from the recent advances in sensor and communication technologies, along with their increasing degree of miniaturization due to microelectronic integration. These systems have been shown to have the potential to revolutionise healthcare systems, which are currently under increasing pressure, due their rising global costs, ageing of the population and associated prevalence of chronic disease (Hao and Foster, 2008). In this sense, the promotion of a shift in healthcare systems from reactive management of illness towards proactive management of wellness is desired (Milenković et al., 2006), supported by innovative, affordable and efficient solutions for personal health monitoring. Many other benefits are envisioned through the widespread availability of these solutions for both patients and caregivers. The quality of life and mobility of monitored patients is increased and the means for detection of early signs of disease are improved by long-term continuous monitoring (Nield et al., 2004). These allow for patients to keep an independent lifestyle in their environment of choice and for caregivers to provide better treatment and prevent further complications.

Among the different physiological signals which can be continuously measured with health monitoring systems, in order to evaluate the health condition of a person, the 12-lead electrocardiogram (ECG) is arguably the most important, since cardiac disease is the leading cause of death and disability in the world. The 12-lead ECG is considered as the gold standard for non-invasive detection of abnormal cardiac rhythms and cardiac diseases such as myocardial ischemia. However, continuous monitoring of the full set of 12 leads of the standard ECG, and the placement of the respective electrodes at their standard locations (which include the distal extremities of the limbs), is unattractive and incompatible with the design requirements of a wearable system for health monitoring, namely unobtrusiveness, comfortable use and user-friendliness. Therefore, most of the wearable health monitoring systems proposed to date are only able to monitor a single lead or a lead subset (e.g. 3-lead ECG composed only of Einthoven leads) of the standard 12-lead ECG (Pantepoulos and Bourbakis, 2010), and thus only a limited interpretation of the

P. Figueiredo C. and M. Mendes P..
TOWARDS WEARABLE AND CONTINUOUS 12-LEAD ELECTROCARDIOGRAM MONITORING - Synthesis of the 12-lead Electrocardiogram using 3 Wireless Single-lead Sensors.
DOI: 10.5220/0003771203290332
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2012), pages 329-332
ISBN: 978-989-8425-91-1

electrical activity of the heart is obtained. This limitation can be critical for the sensibility of the ECG monitoring system on the detection of certain cardiac abnormalities, e.g., ischemic episodes may be only visible in part of the 12 standard ECG leads and may be overlooked (Klootwijk et al., 1998), even during continuous monitoring. Moreover, caregivers could perform more efficiently if the health monitoring system could provide them with the ECG signal in the same fashion in which they were trained to analyse, i.e., the standard 12-lead ECG.

Due to the conflicting design requirements concerning wearable and continuous monitoring of the 12-lead ECG, solutions are needed to allow monitoring the full set of 12 ECG leads, while simultaneously minimising the obtrusiveness of the monitoring system. On this subject, several authors have proposed and studied the synthesis of the 12-lead ECG using reduced lead sets, based on the application a generic or patient-specific transformation matrix, estimated through multiple linear regression, to the lead signals of the reduced lead set (Dower et al., 1988; Nelwan et al., 2004).

The synthesis of the 12-lead ECG using wireless technology was proposed by Trobec and Tomašić (2011), based on a set of 3 differential leads formed by pair of proximal electrodes. However, the impact caused by the use of wireless communications in the performance of the synthesis algorithm was not analysed. In this regard, this work aims to analyse the suitability of a developed wireless network prototype, consisting of 3 wearable single-lead ECG sensors, for application in 12-lead ECG synthesis. The quality of the acquired lead signals is evaluated, as well as the issues caused by the wireless transmission of these independent signals, such as reliability (transmission errors leading to loss of information) and synchronization between nodes.

2 SYSTEM OVERVIEW

The currently proposed system is illustrated in Figure 1, and it has the aim of enabling continuous monitoring of a synthesised 12-lead ECG. It can be seen that the proposed solution is based on a wireless network of three wearable single-lead ECG sensors, placed at different locations and orientations on the chest of the monitored patient. In addition, a coordinating node is used to receive the signals acquired by each of the 3 single-lead ECG sensors, and to forward them via USB connection to a personal computer where the 12-lead ECG is synthesized and displayed. The use of these

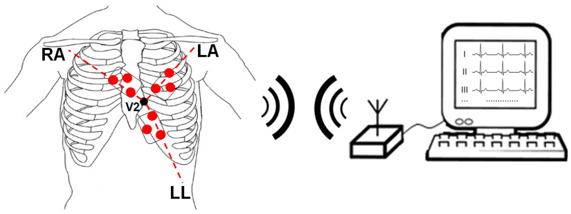

Figure 1: Proposed wireless network of wearable sensors for continuous monitoring of a synthesised 12-lead ECG.

wearable single-lead ECG sensors, combined with the use of wireless technology and an algorithm for 12-lead ECG synthesis based on independent local lead signals, has allowed the design of a wearable 12-lead ECG monitoring system featuring total absence of wired connections, such as electrode lead wires, and which also does not require the monitored leads to be referenced to the same ground.

The synthesized 12-lead ECG is calculated on a personal computer, from the independent single-lead ECG signals obtained by the 3 sensors in the network, using the following linear equation:

$$L_i = M_{i0} + M_{i1} l_{node\ 1} + M_{i2} l_{node\ 2} + M_{i3} l_{node\ 3} \quad (1)$$

where L_i indicates the amplitude of synthesized lead i (i = 1, …, 12 or {I, II, III, aVR, aVL, aVF, V1, …, V6}), $l_{node\ j}$ indicates the amplitude of the lead signal at node j (j = 1, 2, 3) and M_{ij} is the transformation matrix filled with patient-specific coefficients, estimated using multiple linear regression to fit the model shown in (1) to a dataset of a previously measured standard 12-lead ECG (dependent variable) and the three single-lead ECG signals (independent variables) (i = 1, …, 12 and j = 0, ..., 3).

Concerning the currently presented approach, it can be noticed from Figure 1 that the wearable single-lead ECG sensors are centred on V2 and that their monitored local leads are oriented towards the proximal extremities of the limbs. This configuration was selected based on existing evidence that the 12-lead ECG can be synthesized with a fair degree of accuracy (cross correlation coefficients greater than 0.9) using a 3-lead subset composed of leads I, II and V2 (Atoui et al., 2010; Nelwan et al., 2004), even if the Mason-Likar modification of the standard 12-lead ECG is used for the reduction of motion artefacts. The position of each single-lead ECG sensor on the chest of the monitored patient can be moved along the directions indicated by the dashed lines shown in Figure 1, to increase the accuracy of the synthesised ECG or to increase user comfort, as long as these positions are kept constant between different monitoring sessions of each particular user.

3 WEARABLE SINGLE-LEAD ECG SENSOR

Each single-lead ECG sensor within the wireless network is similar and the appearance of their first prototype (Figueiredo et al., 2010) is shown in Figure 2.

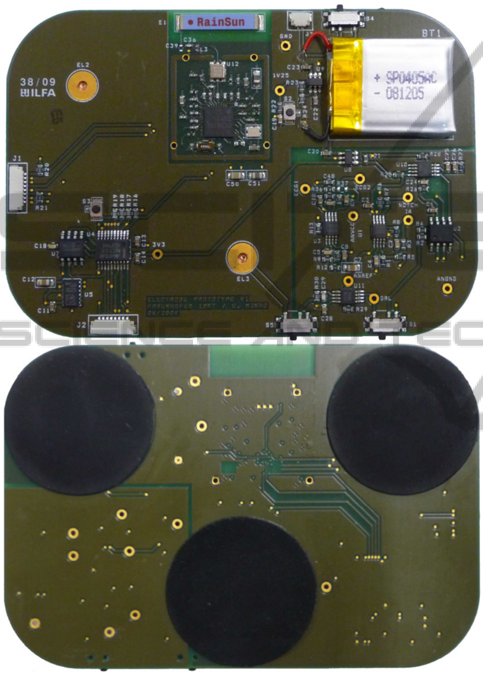

Figure 2: Top and bottom views of the developed wireless sensor node for monitoring of a single modified ECG lead.

The wearable sensor shown in Figure 2 consists of a flexible printed circuit board containing built-in flexible dry electrodes (Steltenkamp et al., 2009) on its bottom layer, which is intended to contact the surface of the chest of the monitored patient. These electrodes do not require skin preparation before use and are therefore suitable for a wearable system. The top layer contains low-power electronics for signal acquisition, processing and wireless communication, making use of commercial off-the-shelf components. The design of these sensors meets the requirements for a wearable system for health monitoring such as: small dimensions, light weight, wireless communication and low power consumption.

The wireless communications between the single-lead ECG sensors and the coordinating node are based on proprietary wireless transceiver and MAC Protocol (Omeni et al., 2008), which operates at the non-crowded 862-870 MHz radio band, and uses a master-slave architecture with collision avoidance and a Time Division Multiple Access (TDMA) scheme. These features not only provide error resilient and low power wireless communication, but also help to keep synchronism between the data transmitted from the different sensor nodes, since the network coordinating node periodically requests data from each sensor node in succession, and only one sensor node is transmitting at a time.

Besides monitoring of a local ECG lead, the wireless sensor nodes also include a triaxial accelerometer and a thermistor for activity and temperature monitoring. Table 1 summarizes the specifications and features of the developed wearable single-lead ECG sensors (Figueiredo et al., 2010).

Table 1: Summary of the specifications and features of the developed wearable single-lead ECG sensors.

Wireless link	Operation frequency	862-870 MHz
	Data rate	50 kbps
ECG lead monitoring	Gain	500
	Resolution	11 bits
	Sampling Frequency	250 samples/s
Triaxial accelerometer monitoring	Range	± 2g or ± 8g
	Resolution	8 bits
	Sampling Frequency	400 samples/s (max.)
Temperature monitoring	Range	20 ºC to 40 ºC
	Resolution	11 bits
	Sampling Frequency	250 samples/s
Power consumption	Supply voltage	3.3 V (minimal)
	Average current consumption	0.98 mA (ECG mode)
		1.43 mA (ECG + accelerometer mode)

4 RESULTS

4.1 Measurement of Single-lead ECG Signals

A five second period of a modified ECG lead, obtained by the developed single-lead ECG sensor is shown in Figure 3. The obtained signal has suitable quality and signal to noise ratio for the intended ECG monitoring application, allowing different features of the ECG signal to be detected, such as the QRS complex, T wave and the ST interval.

4.2 Wireless Link Performance

The reliability of the wireless communications between the sensor nodes and the network coordinating node was tested by evaluating the number of communication errors occurred over time.

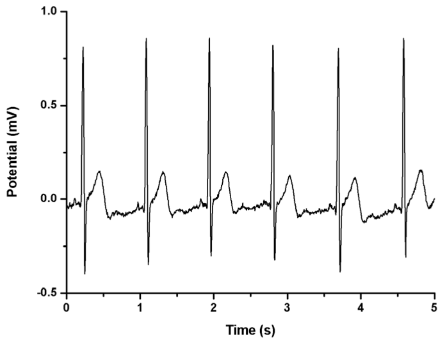

Figure 3: ECG lead signal acquired by the developed wearable sensor.

Table 2 shows a list of different statistics obtained during a testing period of one hour, within which the 3 wireless sensor nodes were performing signal acquisition and transmitted their monitored data when requested by the network coordinating node, following a TDMA communication scheme.

Table 2: Statistics of error performance in wireless communications within the developed network, during a testing period of one hour.

Connection losses	2
Packets lost due to link errors	60
Duplicate packets received	10
Total number of generated packets/TDMA slots	1383
Packet error rate	5.1%

The obtained packet rate of 5.1% is considerable, although it could be acceptable for continuous long-term monitoring applications, where loss of data is less critical.

5 CONCLUSIONS

From a preliminary analysis of the developed system, it is expected that the use of a wireless network of single-lead ECG sensors, using a protocol based on TDMA and operating in a less crowed band, could provide reliable support for continuous monitoring of independent single-lead signals and for continuous 12-lead ECG synthesis.

Future work will involve testing of the accuracy of the proposed system for 12-lead ECG synthesis in volunteers and the development of a new miniaturised version of the single-lead ECG sensors. Moreover, tests should be performed to evaluate up to what degree the data losses caused by errors in wireless communications affect the accuracy and the performance of the system for continuous monitoring of a synthesized 12-lead ECG.

ACKNOWLEDGEMENTS

This work was supported by the Portuguese Foundation for Science and Technology under grant SFRH/BD/40341/2007.

REFERENCES

Atoui, H., Fayn, J., Rubel, P., 2010. A Novel Neural-Network Model for Deriving Standard 12-Lead ECGs From Serial Three-Lead ECGs: Application to Self-Care. *IEEE Trans. Inf. Technol. Biomed.*, 14(3), 883-890.

Dower, G. E., Yakush, A., Nazzal, S. B., Jutzy, R. V., Ruiz, C. E., 1988. Deriving the 12-lead electrocardiogram from four (EASI) electrodes. *J. Electrocardiol.*, 21, 182-187.

Figueiredo, C. P., Becher, K., Hoffmann, K.-P., Mendes, P. M., 2010. Low Power Wireless Acquisition Module for Wearable Health Monitoring Systems. *Proc. 32nd Ann. Int. IEEE EMBS Conf.*, 704-707.

Hao, Y., Foster, R., 2008. Wireless body sensor networks for health-monitoring applications. *Physiol. Meas.*, 29, R27-R56.

Klootwijk, P. et al., 1998. Comparison of usefulness of computer assisted continuous 48-h 3-lead with 12-lead ECG ischaemia monitoring for detection and quantitation of ischaemia in patients with unstable angina. *Eur. Heart J.*, 18(6), 931-940.

Milenković, A., Otto, C., Jovanov, E., 2006. Wireless sensor networks for personal health monitoring: Issues and an implementation. *Comp. Commun.*, 29, 2521-2533.

Nelwan, S. P., Kors, J. A., Meij, S. H., Bemmel, J. H. v., Simoons, M.L., 2004. Reconstruction of the 12-lead ECG from Reduced Lead Sets. *J.Electrocardiol.,* 37, 11-18.

Nield, I., Heatley, D. T. J., Kalawsky, R. S., Bowmann, P. A., 2004. Sensors Networks for Continuous Health Monitoring. *BT Technol. J.*, 22(3), 130-139.

Omeni, O. C., Eljamaly, O., Burdett, A. J., 2007. Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks. *Proc. 4th IEEE-EMBS Int. Summer School & Symp. Medical Devices and Biosensors*, 29-32.

Pantepoulos, A., Bourbakis, N. G., 2010. A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis. *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, 40(1), 1-12.

Steltenkamp, S., Becher, K., Doerge, T., Ruff, R., Hoffmann, K.-P., 2009. Electrode structures for acquisition and neural stimulation controlling the cardiovascular system. *Proc. 31st Ann. Int. IEEE EMBS Conf.*, 5478-5481.

Trobec, R., Tomašić, I., 2011. Synthesis of the 12-Lead Electrocardiogram From Differential Leads. *IEEE Trans. Inf. Technol. Biomed.*, 15(4), 615-621.