Wearable monitoring of cardiopulmonary activity through radiant sensing

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***Abstract*— This paper is concerned with wearable monitoring of cardiopulmonary activity through radiant sensing. Here we propose two systems consisting of a multi-modal broad-band piezoelectric transducer based on PVDF polymer and system-on-a-chip UWB radar both integrated into a textile belt wrapped around the chest and.**

The multi-modal transducer is innovative in that only one sensitive element is employed as ultrasound transceiver. It is excited by suitable pulses to emit an ultrasonic wave, which penetrates the body and receives the echo signals bouncing off the biological interfaces having different acoustic impedance. The transducer thickness is thin enough to assure a good adaptability to the biological site, and it is equipped with an advanced control unit. If jointly used along with an ECG wearable Holter, this transducer can be used to provide an exhaustive picture of the health status of the subject in the diagnostic and prognostic domains.

The second system here presented is a wearable system-on-a-chip UWB radar for health care systems is presented. The system consists of a wearable wireless interface including a fully integrated UWB radar for the detection of the heart beat and breath rates, and a IEEE 802.15.4 ZigBee radio interface. The principle of operation of the UWB radar for the monitoring of the heart wall is explained hereinafter. The results obtained by the feasibility study regarding its implementation on a modern standard silicon technology (CMOS 90 nm) are reported, demonstrating (at simulation level) the effectiveness of such an approach and enabling the standard silicon technology for new generations of wireless sensors for heath care and safeguard wearable systems.

Introduction

The aim of the work here proposed is to research avant-garde heart activity monitoring systems in order to obtain a more complete status of the heart. Work results are constituted of two possible systems based on two different technologies. Moreover, it describes how the cardiac physiological variables acquired are connected together over a long time period acquisition sequences and more specifically discussing the integration of the sensor in textile substrates for producing a wearable system capable of monitoring the heart and respiratory activity during different physical situations. According to the World Heart Organization (WHO), CardioVascular Disease (CVD) constitutes the most common cause of death in the world, as well as for a third of all deaths worldwide. An investigation of the heart status becomes essential in CVD prevention and diagnosis. A comparative analysis between the behavior of the organs around the heart (i.e. the respiratory apparatus) is necessary because of their strong correlation. In particular, biomedical signal analysis research of the last few years has shown how a large quantity of information on sympathetic and parasympathetic systems can be obtained by analyzing a given signal as the correlation between respiratory and heart activity signals. Considering that the most used portable cardiac monitoring system (Holter) used over a long period of time currently checks only the electrical status of the heart, the possibility of obtaining a more complete picture of the heart status led us to use the echocardiographic exam for carrying out a more specific, non-invasive investigation of the heart. Latest research is aimed at moving health services towards the patient with a consequential overhead reduction and improving health services quality. In the last few years, wearable systems based on "e-textile" substrates have increasingly become important in the biomedical research area. The successive analysis shows how a multi-signal wearable heart monitoring system to prevent and diagnose CVD could be helpful. This research is focused on the development of a wearable system based on a single tranceiver. The tranceiver must have high sensitivity. Such system introduces innovative aspects in microelectronic technologies, in multi-signal acquisition and elaboration routines, in the sensor technique such as multi-modal tranceivers, in textile integration and in medical signals picture where provides many correlated vital signals and introduces mechanical information.

This work proposes the analysis of two particular systems based on two different principles. The first is based on a particular bimodal ultrasonic transducer and the second is based on an Ultra-Wide-Band (UWB) radar. The particular multi-modal transducer is based on PVDF polymer whose wide band of sensitivity allows of generating ultrasound waves and receiving back-scattered echoes from the heart wall. This information is integrated by the ECG recordings through textile electrodes. The second system idea consists of two embedded transceivers: the first (the sensor) is a Ultra WideBand (3.1-10.6 GHz) short-range micro-power radar for the non-invasive detection of the heart and breath rates, and the second is a low power Zig-Bee (standard IEEE 802.15.4) radio link that allows us to send the detected information to the remote acquisition and processing unit (or within the personal area sensors network). In detail, the Ultra Wideband (UWB) radar detects the heart and breath rates by sending a very short electromagnetic pulse (hundreds of picoseconds) and detecting the echo-pulse generated by the reflection at the heart wall (due to the different characteristic impedances). Each electromagnetic pulse (of a proper sequence) transmitted toward the heart will be partially reflected and, after a time delay depending on the distance from the heart wall, the echoes will be received by the antenna, detected and isolated from all other interferences in order to extract the information concerning the heart and breath rates.

Ultrasound System

The core of this system is a multi-modal transducer based on PVDF polymer whose broad band of sensitivity jointly at low value of its figure of merit (Q) makes the transducer sufficiently able to record vital signals in a wide frequency range. Indeed, the transducer is sensitive at low frequency sources, such as breathing signal and heart apex pulses, and capable of generating ultrasound waves and receiving back-scattered echoes from the wall of the heart. In order to assess the performance of the system, it is also equipped with an ECG detector based on fabric electrodes.

Cardiac ctivities in basal conditions is located in the former ranges from about 0.9 to 2 Hz.

The transducer is placed into a textile band wrapped around the chest and is connected to a suitable wireless electronics placed around the waist. The system, supplied by a battery, sends signals coming from the transducer to a PC through an analog-to-digital acquisition board.

The transducer used in the system consists of a PVDF piezoelectric film. It is constituted of two electrodes (1cm x 1cm) separated by PVDF film (1cm x 1cm x 100μm) (see fig. 1) and backing material (1,2cm x 1,2cm) positioned behind the electrode on the opposite side of the body. As high voltage impulses are required to excite the transducer, it is equipped with an electrically insulated outer covering.

Because the polymer shows a pyroelectric behavior, a thermal contribution can affect the output voltage, because of its low value, it was disregarded for the purpose of this work Transducer characterization, in terms of piezoelectric coefficients, electrical and mechanical parameters and figure of merit, is beyond the purpose of this work.

Piezoelectric materials with low Q factor are characterized by having a broader bandwidth than those with high Q factor with narrow resonant peaks. The transducer here used exhibits a low Q factor and hence allows us to use the same single transducer as an ultrasound transceiver at high frequency. An ultrasound transceiver investigates heart wall movements with a working frequency range of about 1-10 MHz In this paper, a near field investigation is used. The goal is to detect the echo coming back from the heart wall passing into a scattered wave region.

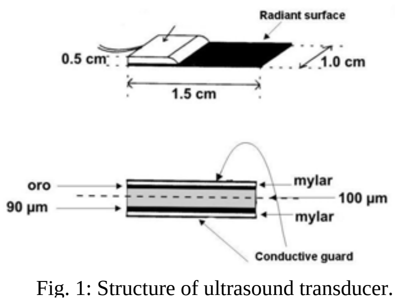

Fig. 1: Structure of ultrasound transducer.

As PVDF exhibits a low Q, the transducer results to be a better receiver rather than transmitter. The low value of this factor is due to the loss properties of the material [1-3]. Notwithstanding the low value of energy transfer from the transducer to the human body, it is experimentally shown that it is sufficient to investigate heart wall movement.

In order to get a clear view of the heart, the transducer should be positioned at the 5th intercostal space between bones and lungs. This implies a careful and accurate orientation and position of the transducer [3]. Moreover, as the power consumption for a continuous ultrasound monitoring is too high to be supported by electric batteries, the system is thought to be used intermittently either during fixed periods or upon the detection of critical events detected by low frequency analysis. The high frequency part is comprised of a microcontroller that under specific conditions enables the active element to generate ultrasound impulses and receive the echo signals coming back from the acoustic interfaces. Afterwards, the received signals are amplified and filtered, and through a data acquisition board (National Instrument 6115 S-series) they are sampled and sent to a computer.

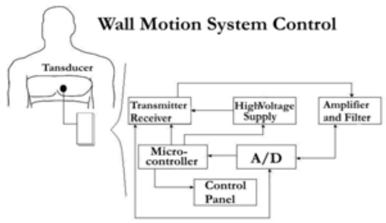

Fig. 2: Scheme of the ultrasound system.

EXPERIMENTAL RESULTS

The experimental section is divided into two phases according ultrasound transducer functionality. The acquisitions were repeated on four subjects over a period of fifteen seconds. The goal is to show that the transducer is able to provide reliable information on cardiac activity. In this preliminary phase a limited group of subjects volunteered to participate in these experiments. Deeper statistical analysis will be planned in the next developments.

The electronic device for US investigation was realized according to the most used echo-graphic standard technique. The dimensions and the shape of the piezoelectric element make it sensitive to the back-propagated echoes in the near beam field only, disregarding the back-scattering phenomena.

The device was developed to have low power consumption and be small in dimension in order to be easily integrated into fabrics and to ensure durability over a long period of time by using a 6V battery supply. The block diagram was already shown in Fig.2. In particular, two rechargeable batteries are used, one for the high voltage generation and the second for the remaining part of the circuit. Next, heart wall depth and movement monitoring were investigated.

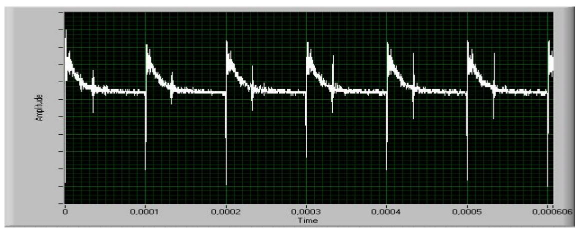

Fig. 3: Acquisition ultrasound interface: in the graph the exciting and relative echoes are reported.

The ultrasound system is comprised of a US transducer coupled to the chest of the patient by means of an ultrasound transparent membrane, thus obtaining good coupling acoustic impedance between the transducer and the human body, see Fig.2. In Figure 3 a train of ultrasound impulses showing the echoes coming back from the wall of the heart is represented. In this Figure the time delay between the exciting impulse and the received echo is converted into spatial distance, as shown in the upper curve of Figure 5. This last Figure shows the resulted movement of the heart wall (expressed in m) compared with the ECG signal acquired at the same time. In support of the effectiveness of the system, it is worthwhile pointing out that each part of the curve comprised between two relative minimal points corresponds to a complete cardiac cycle.

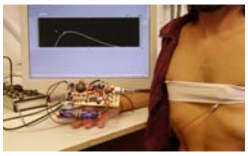

Fig. 4: Testing of the US prototype on a living subject.

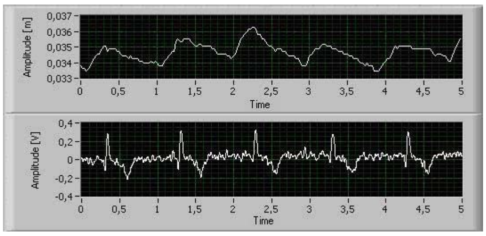

Fig. 5: Upper graph shows the spatial distance over time of the heart wall expressed in cm. Lower graph shows the ECG signal simultaneously acquired.

UWB RADAR

The recent advances in the standard CMOS silicon technologies, has led up to highly miniaturized, low cost, and ultra low power integrated circuits. This fact allows the realization of high-potential systems-on-a-chip for a large number of new applications. One of the most interesting fields of application of fully integrated systems-on-chip is represented by the emerging wireless body area networks (WBANs) for the human health care and safeguard. The wearable UWB radar systems allows us to monitor directly the mechanics of heart and chest, instead of their indirect measurements by means of electrocardiograph (ECG) or echocardiograph systems.

This paper focuses the aforementioned topic and reports the idea of a novel wearable wireless interface for monitoring the heart wall and chest movements, for a contactless detection of the heart and breath rates.

WEREABLE WIRELESS INTERFACE FOR HEART MONITORING: SYSTEM OVERVIEW

In February 2002 the Federal Communications Commission (FCC) gave the permission for the marketing and operation of a new class of products incorporating ultra-wide-band (UWB) technology [4]. Since UWB systems are intended to operate in regions of 3.1-10.6 GHz in which other services are already operating, the mask of the maximum power spectral density (PSD) allowed for UWB devices has been set to very low values (-41.3 dBm/MHz in the 3.1-10-6 GHz band).

Particularly, we are interested in realizing UWB radar sensor for the monitoring of the heart wall and chest movements, in order to detect in real time the heart and breath rates, respectively. The modern silicon technologies (the transistors of the standard CMOS 90 nm technology have cut-off frequencies higher than 150 GHz) allow us to realize ultra-small and ultra-low-power wireless UWB sensors for WBAN applications. WBANs consist of sensor networks, in which the sensors are placed around the human body in order to monitor constantly the vital parameters.

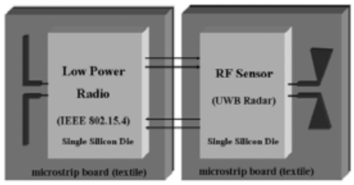

Fig. 6. Wearable wireless interface for the heart monitoring: system idea.

Fig. 7. Inner garment

The information collected by these sensors can be sent, by means of radiofrequency data link, toward remote data acquisition and signal processing units or even to a personal server, which can forward the data to the medical centres and hospitals by means of internet.

The overall system idea is shown Fig.6. It consists of a fully integrated UWB radar sensor and a low-power radio interface. Both for the radar system and radar interface, we deal with their realization by means of a standard CMOS 90 nm by STMicroelectronics (STM). In the scheme of Fig.6 each antenna is realized on a microstrip substrate; however, in a most advanced realization, they can be realized directly by means of proper conductive layers tissued within clothes [6]. In particular, such a sensor will be included into the inner garment worn by emergency operators, which is shown in Fig. 7. The proposed fully integrated UWB radar (Fig.8) detects the heart and breath rates by sending very short electromagnetic pulses (hundreds of picoseconds) and detecting the echoes generated by the reflections at the heart wall (due to the different characteristic impedances between the heart muscle and the blood flowing inside the heart itself). The basic principle of operation is described in [7], [8]. It is worth mentioning that, the UWB pulses (3.1-10.6 GHz) are not influenced by clothes or blankets and they can be exploited efficiently for the monitoring of the heart rate [8]. Moreover, the UWB pulses have a very low-density spectrum if compared with the narrow band conterparts, reducing drastically the risk of cellular ionization on the human beings [9]–[14].

SYSTEM-ON-A-CHIP UWB RADAR SENSOR FOR THE HEART AND BREATH RATES MONITORING

The main block of the proposed wearable wireless interface for the monitoring of the heart is represented by the UWB radar sensor. The radar architecture is shown in Fig.8. In detail, the system operates by sending extremely short electromagnetic pulses toward the heart.. A pulse repetition frequency (PRF) greater than 1 MHz allows us to consider the heart almost motionless between two consecutive pulses.

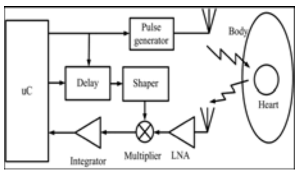

Fig. 8. Block diagram of theUWB radar

The output voltage of the receiver front-end is averaged by integrating over a large number of pulses. This operation allows us to increase significantly the signal-to-noise ratio at the output of the receiver. Moreover, the amplitude of the continuous output signal of the integrator is related to the time-varying position of the moving object under observation (the heart wall, in our case). Thus, the output signal provided by the integrator includes the tones of the heart beat and the breathing frequency.

A. *Summary of the Feasibility Study of the UWB Radar Sensor*

In order to demonstrate the feasibility of such a UWB radar sensor, a system analysis has been carried out by means both a theoretical model and simulations by means of CAD tools. Firstly, the theoretical analysis has been carried out. We have developed a theoretical model of the channel in which the pulse propagates. In order to validate the theoretical model of the radar, the overall system has been simulated with the Ptolemy simulator within Agilent ADS2005A™. Each building block was characterized by frequency response and noise contribution achievable realistically with the CMOS 90 nm process. Simulation results have confirmed the feasibility of a fully integrated system-on-a-chip UWB radar sensor on silicon. The radar signal is compliant with the FCC mask for the UWB medical imaging systems. The voltage at the output of the integrator is shown in Fig.9. This signal has the same frequency of the time-varying surface (i.e. the heart wall) under observation. A heart movement having a period of 20 ms has been considered.

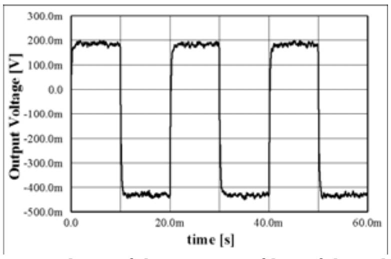

Fig. 9. Output voltage of the integrator filter of the radar sensor.

CONCLUSION

The systems here proposed showed good performance and produced satisfactory results. Indeed, the system based on a bi-modal PVDF transducer was able to perform ultrasonic investigation providing helpful cues on the cardiac status. The aim of the system was to implement a wearable monitoring system using only one US transducer element working at high frequency detecting signals such as heart wall movements. Frequency investigation showed the movements of the heart wall, e.g. spatial length, expressed in centimeters, and the signal synchronism was partially tested through a simultaneous ECG signal. The quality of these results depends on the exact parallelism between the US and heart wall, the sampling time at the high frequency acquisition and the algorithm implemented to localize the returned echo. Nonetheless, several issues should be more deeply addressed. As the system should be wearable and used for a long time, the relative body-transducer displacement as well as skin-electrode mismatch are crucial aspects. Skin-transducer or skin-electrode interfaces, indeed, should have a good electric coupling and, at the same time, should be comfortable for the subject wearing the system. The system is thought to be used in emergencies (intensive care, post-operatory treatment) or for transporting patients in serious conditions, but it cannot be used in daily activities because body motion can produce significant artefacts in the signals. Future work is addressed to remove noisy artefacts and further miniaturize the system for making it more comfortable and wearable. The second system is based on the recent advances in silicon CMOS technologies, which allow for the realization of more and more miniaturized, low-cost and low-power integrated systemon-a-chip sensors. The output signal has the same frequency of the simulated movement for the heart wall. A time-moving surface with a period of 20 ms has been considered for the simulation (this time period is short with respect to the real heart movement in order to reduce the simulation time this does not impair the analysis since the radar reaches the steady state widely within 10 ms). These sensors can be employed in the wireless body area networks for advanced and continuous monitoring of vital parameters. Particularly, the system overview of a next generation wearable wireless sensors for human health care and safeguard has been herein presented. Such a system is composed of a novel fully-integrated ultra-wide-band radar sensor for the detection of the heart and breath rates and a low-power radio interface (IEEE 802.15.4, ZigBee), which collects the data provided by the sensor and sends the data to an acquisition unit or even via internet by means of a personal server. Thus, the physiological data of a patient can be sent in real time to the hospital and the medical doctors could operate in time in the occurrences of anomalous monitored vital parameters. A study on the feasibility of the UWB radar on silicon technology (CMOS 90 nm) for the detection of the heart and breath rates has been carried out, and simulation results have shown the feasibility of the proposed single-chip radar sensor. Future works addresses antenna design, channel model verification, building block design and their co-integration on CMOS 90 nm.

ACKNOWLEDGMENTS

The authors are grateful to the European Union for its financial support through the European Project ProeTex within the 6th FPQ (project FP6-2004-IST-4-026987).

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