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# Performance Analysis and Early Validation of a Bi-modal Ultrasound Transducer

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*Abstract*— **In this paper we report on results from experiments performed on a bi-modal piezoelectric transducer used both as an active ultrasound transceiver and a passive acoustic sensor. [1]The transducer, which has a low Q factor in order to exhibit a sufficiently broad bandwidth, will be integrated into a wearable system [2]. In particular, it is placed, along with ECG fabric electrodes, within a textile belt wrapped around the chest. The transducer behaves as an acoustic sensor at low frequency and as an ultrasound transducer at high frequency. The low-frequency acoustic signals were compared with the analogue signals acquired simultaneously by commercial biomedical sensors. These signals provide information about the respiratory activity and heart apex pulse. A comparative analysis was performed both in the time and frequency domain and results were discussed.**

**Moreover, the same transducer used at high frequencies is able to generate ultrasound signals which can bounce off the target organ, the heart, and receive the back-propagated echoes. The experimental validation was done by means of a comparison between the spatial interval inferred from time delay of the return echoes detected by the transducer and the actual distance from the target. This information, in addition to ECG signals, can provide helpful cues for the cardiac status of the subject, both in terms of prevention and diagnosis.**

## I. Introduction

NOWADAYS, the ultrasound (US) systems for clinical purposes are heavy, bulky and not wearable. The challenging research activity we endeavoured to perform is to realize a wearable, portable and automatic ultrasound system integrated with a breath and heart apex pulse system detector, which does not require human contribution in positioning and directing the acoustic waves.

The system innovation is the integration of a passive sensor working at low frequency that is able to acquire cardiac sound, breathing signal and heartbeat rate with an active system able to transmit and receive ultrasound signals for detecting heart wall movements. A suitable switching system allows changing from one modality to the other.

This low Q factor is the primary requirement in order to provide the bimodality feature for the transducer. Low Q factor is defined as the ratio between the centre frequency (resonant frequency) and bandwidth, implying a broader working frequency range.

The system is comprised of a textile band wrapped around the chest containing the US transducer and three electrodes for ECG acquisition. The ECG signal was considered to provide the interlock signal in the ultrasound investigation. Moreover, it provides information about the electric behaviour of the heart and can enrich the clinical picture of the cardiac activity adding to the signals acquired by the US transducer.

## II. Material And Methods

The transducer [3] element used in the system here proposed is based on a PVDF [4] piezoelectric element. The low Q factor implies a large frequency bandwidth and represents a fair trade-off in acquiring significant signals either at high or low frequencies [5].

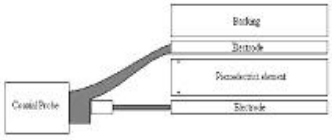


Fig. I: Model of the ultrasound transducer

The US transducer is a custom model transducer based on the Oligashi, patent (see fig. I).

The system is based on a textile band containing the transducer and the ECG electrodes [2]. Through electric paths, realized on a textile substrate as well, the electrodes are connected to an electronic board inserted into a belt rounding the waist. Currently, the ECG electrodes are realized on a textile substrate and integrated into the fabric band, while the transducer is pasted or sewn onto the band, positioned as in Figure 2a and on the left side of Figure 3, which shows the block diagram of the system at low frequency, while on the right side the US working scheme is reported. From the medical literature, it is known that sounds propagate [7] inside the body through non-homogeneous internal tissues.

When cardiac sounds come up to the body surface, they create particular listening zones (points of maximum intensity) (see fig.2b). Acoustic waves [8] generated in cardiac rooms can propagate across the viscoelastic medium (soft tissues) in three

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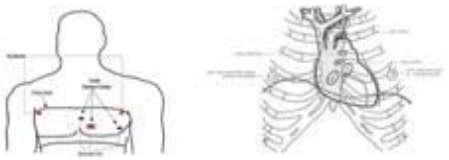
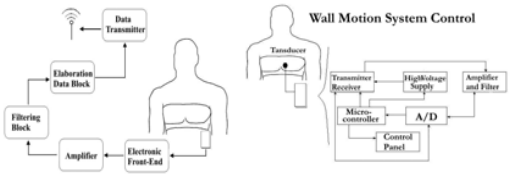


a) b)

Fig.2: a: A possible configuration in positioning sensors and transducers: b) Points of maximum sound intensity [6], [7].




a) b)

Fig. 3: a: Schematic low frequency receiver block; b: Scheme of the ultrasound system.

ways: longitudinal waves (~1500m/s), transverse waves (~15-20m/s), and surface waves (~20m/s). The microphone (transducer) placed on the patient skin allows to capture the waves from the chest surface in the audible range (0.05 Hz - 20 KHz). In addition, as the piezoelectric transducer is positioned in direct and tight contact with the chest, it is also sensitive to chest movements, which are strongly related to respiratory activity (frequency much less than 1 Hz). Hence, by separating the contribution at different frequencies [10], it is possible to discriminate different significant information. The same transducer used for acquiring signals at low frequencies is also employed to inquire into heart wall movements (see fig.3b). Sometime, in cardiac diseases, anomalous mechanical heart behaviour occurs earlier than the electric signal alteration. In this context, a device able to continuously monitor the mechanical activity of the heart could provide important and helpful information to prevent critical cardiac injuries. Nevertheless, the power consumption of the electronics is too high to allow a long duration of the battery supply. Hence it is expected that the transducer will be used intermittently either in established periods or upon detection of critical events detected by ECG signal.

In order to assess the transducer performance, it was compared with a commercial biomedical sensor. The commercial system used was the Biopac system [11] and in particular we used the MP35/30 instrument. Biopac System Inc. instrumentation is designed for research-oriented life science investigations. The MP35/30 in an electrically isolated data acquisition unit is designed for biophysical measurements. The software used to realize the elaborating routines is the National Instrument LabView software ver.8 [13]. The transducer switching behaviour is governed by a microcontroller. It checks the subject status through the low frequency signals, and when an anomalous event occurs in every signal acquired (shape, frequency, period, etc.) it activates the US system to emit an impulse train that analyzes the mechanical heart wall movement. The electronic acquisition block is divided into two parts. The low frequency electronic part is composed of an amplifying block, filtering block and data acquisition board (National Instrument S-series 6115). The high frequency part is comprised of a microcontroller (which can be substituted in the future with a PSoC device) that under specific conditions enables the activation of the piezoelectric element to generate ultrasound impulses and to receive the echo signals coming back from the acoustic interfaces. Signals are gathered by an acquisition board (National Instrument PC-mio series), suitably sampled and sent to a computer.

## III. MATH

The goal of this work was to compare the signals obtained by our bi-modal US system with the signals obtained by a commercial system currently used to acquire vital signals. The comparison was done both in the time and frequency domains aiming at identifying similarities in terms of morphology and equivalency of the frequency components, respectively.

Low frequency components include only cardiac sounds, breathing and heart apex pulses. In Figure 6 the preliminary results are reported showing the ECG signal (lower figure) and the output of the transducer used as sensor (upper figure). In the lower figure it is worthwhile noting two different contributions: respiratory frequency, c.a. 14 ppm (pulses per minute), and heartbeat, c.a. 60 ppm. In addition, in correspondence to each ST segment in ECG signal, the sensor output signal shows a peak which is related to the heartbeat. The delay with respect to the QRS complex is due to how long the signal takes to go from the internal source to the peripheral listening points. By filtering the signal, the heart apex pulse contribution is separated from the breath content. Signals acquired by both devices (Biopac system and Bi-modal US system) are: breathing signal, heart apex pulses and ECG as reported in Figure 5 and Figure 6 in the time domain presentation. After the digitalization of the signals, an FFT algorithm [10] was implemented and the frequency analysis was considered. Particular attention has been paid to the safety of the subject. In the Biopac system the digitalization of the signals was done inside the Biopac instrument, while for the Bi-modal US transducer system it was performed by a National Instrument acquisition board S-Series 6115 [13]. All experiments were done *in vivo* on a human subject. The signals were acquired for about 30 seconds and sampled at 1 KHz. The comparison of the systems was done observing the same physiological phenomenon.

The Biopac band respiratory transducer was located on the chest, while the Biopac pulse detector was placed on a finger. Our fabric band with the piezoelectric transducer (see fig.4)

was fastened around the chest. In the commercial system all channels were acquired in AC mode. On the contrary, in our bi-modal US system breathing signal, heart apex pulses were acquired in common mode acquisition. In spite of the commercial system which acquires each signal though different sensors, our system is able to acquire the analogous signals with only one sensor [12]. In the description of the commercial system acquisition channels: Pulse acquisition channel: Gain = 5000; a first order LP filter to 66.5Hz with Q = 0.5; a first order HP filter to 0.5Hz. Breath acquisition channel: Gain = 1000; a first order LP filter to 66.5Hz with Q = 0.5; a first order HP filter to 5Hz.

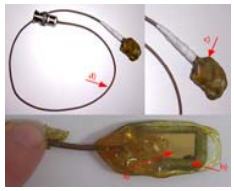


Fig.4 a: Ultrasound Transducer;

A single signal comprised of breath and heart apex pulse was acquired by a charge amplifier with unitary gain to avoid the saturation of the amplifier without external frequency cutting. The signals in the time domain are shown in Figure 6 [12].

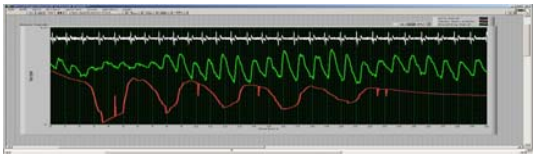


Fig.5 Signals acquired by Biopac system; from top to bottom: ECG signal, heart apex pulse, breathing signal.

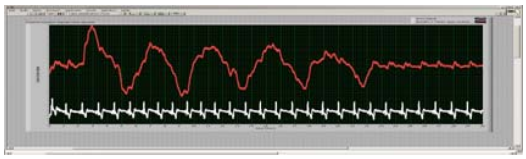


Fig. 6 Signal obtained by the Bi-modal US System; from up to bottom: breathing signal added heart apex pulse, ECG signal.

In order to separate the breathing content from the heart apex pulse information two IIR second order discrete filters [11] were implemented: a low pass Butterworth filter with $f_T$ = *0,5Hz* reported in fig.8a and a pass band Butterworth filter with $f_L$ = *0,9Hz* and $f_H$ = *1,1Hz* with Q = 5 depicted in Figure 8b. In the time domain analysis, it is worthwhile noting that, though the breathing and heart apex pulse filtration added a phase shift introduced by the filters (see fig.8b), the output signal morphology is very similar to signals acquired by the Biopac system (see fig.7).

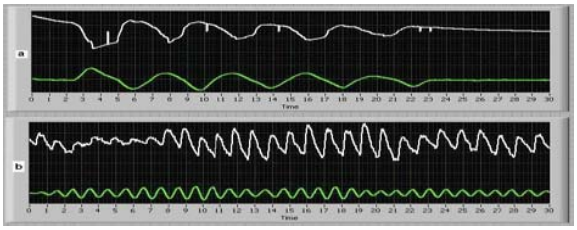
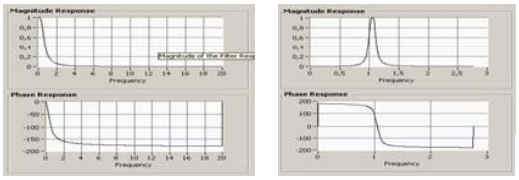


Fig.7 a: Upper graph: Biopac breathing signal, lower graph: US filtered breathing signal; b: Upper graph: Biopac heart apex pulse, lower graph: US filtered heart apex pulse.



(a) (b)

Fig.8 a: Low Pass Butterworth filter; b: Pass Band Butterworth

In order to perform an exhaustive signal analysis we have also investigated the frequency signal behaviour. We have implemented an FFT [10][13] algorithm both for the Biopac signals and for the signals acquired by the Bi-modal US System. Shown in the figure below is the comparison of the frequency components of both breathing signals and heart apex pulse signals:

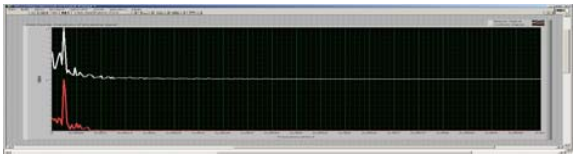


Fig.9 FFT of Breathing signal s; from up to the bottom: FFT of the biopac breathing signal, FFT of the US breathing signal;

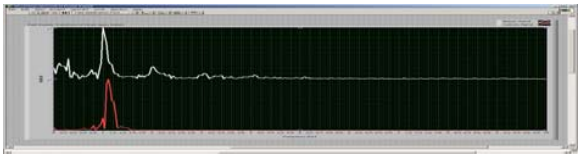


Fig.10 FFT of Heart apex pulse signal; from up to the bottom: FFT of the Biopac Heart apex pulse signal, FFT of the US Heart apex pulse signal;

The FFT algorithm was applied to the signal magnitude without previously windowing or averaging operation. As it can be seen in Figure 9 and Figure 10, the frequency content of the signals coming from our system and the Biopac system is the same, according to a satisfactory similarity in morphology (fig.7). At high frequency, ultrasound acquisitions were made through a US transducer coupled to the chest of the patient by means of an ultrasound transparent gel, thus obtaining good coupling acoustic impedance between the transducer and human body. Figure 11 shows in the upper graph an impulse ultrasound train where the echoes coming back from the wall of the heart can be noticed. It is worth pointing out that the temporal distance between the exciting

impulse and the received echo increases with time. This phenomenon depends on the movement of the heart. The lower graph shows the power spectral density of the signal. Figure 12 shows the path of the heart wall compared with the ECG signal acquired at the same time. The path was calculated using the US velocity inside the body and the time interval of the echoes returning from the excited impulse. Moreover, the ultrasound system was experimentally tested on a suitably designed device, where a sample of PolyVinyl Alcohol (PVA) was used as means through which the ultrasound beam propagated. The PVA thickness was theoretically detected and compared with the actual one. It is worthwhile noting that PVA gel exhibits acoustic impedance similar to that of the human body (see fig. 13) coustic impedance similar to that of the human body (see fig. 13).

## CONCLUSION

The system here proposed showed good performance and produced satisfactory results. Indeed, the system was able to acquire cardiac low frequency signals as well as 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

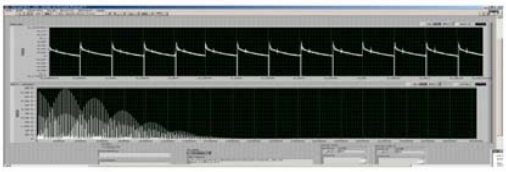


Fig. 11: Acquisition ultrasound interface: in the upper graph the exciting and relative echoes are reported, in the lower graph Power Spectral Density is showed.

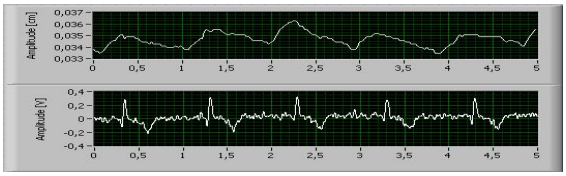
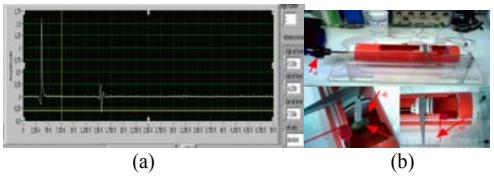



Fig. 12: Upper graph shows the spatial distance over time of the heart wall expressed in cm. Lower graph shows the ECG signal simultaneously acquired.



(a) (b)

Fig. 13: a: Return echo by the PVA sample; b: System measurement used for comparing the measured PVA thickness with the theoretical estimated value.

working in two modalities: either low frequency to acquire signals such as cardiac sounds, breathing and beat-rate or at high frequency detecting signals such as heart wall movements. The comparison results with the commercial instrument at low frequency and with the distance measured for the high frequency have shown a good correspondence both in the time and frequency domains. These conclusions are very relevant considering that the original signals did not undergo conditioning, but were directly transformed.

This high frequency investigation has shown the movement of the heart wall, e.g. spatial length, expressed in cm, and this data was thereby verified simultaneously by the ECG. The accuracy of these results depends on exact parallelism between the US and heart wall, the sampling time at the high frequency acquisition and the algorithm implemented to localize the return 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 the 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. As the system is thought to be used by a subject while doing usual daily actions, motion body can produce significant artefacts in the signals. These drawbacks can be partially overcome by improving the skin-electrode adherence, in terms of mechanical coupling and materials used.

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