



# Associação Portuguesa de Engenharia de Áudio

## Secção Portuguesa da Audio Engineering Society

Artigo Apresentado no 12º Encontro da APEA  
8 e 9 de Outubro de 2010 Universidade de Aveiro

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## DSP-based Multi-channel Stethoscope

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### ABSTRACT

Heart diseases have become, since 1985, the second cause of death worldwide [1]. The development of auxiliary diagnosis tools that help healthcare professionals is essential to obtain within a very short range of time efficient information about the health condition of a patient, particularly regarding heart diseases. Currently, most medical procedures are based on clinical information obtained from electronic systems and computers. In this context, it was developed a multi-channel digital stethoscope that includes Internet connection capabilities. Thus, we intend to demonstrate that is possible multiple acquisition of high quality heart sounds and its subsequent transmission via Internet. The main component of the developed hardware is a DSP (Digital Signal Processor). Using a DSP we aim to achieve greater flexibility and reliability by introducing customizable channel equalization in the signal path, in order to obtain signals of high quality audio. Since there are no standard tests to assess the quality of stethoscopes [2], the performed tests focused on the electrical part of the device, leaving to future work its characterization as a whole. This article describes the hardware developed for the heart sound acquisition system, including digital signal processing and communication modules. Tests were made to the equipment electrical characterization based on procedures commonly used in the evaluation of audio equipment.

### RESUMO

As doenças do coração tornaram-se, desde 1985, na segunda causa de morte a nível mundial [1]. O desenvolvimento de sistemas e meios de diagnóstico que permitam aos profissionais de saúde obter de forma rápida e eficiente o máximo de informação acerca da condição de saúde de um paciente é indispensável, em particular no que diz respeito a doenças do coração. Actualmente, a maioria dos actos médicos são efectuados com base em informação clínica obtida a partir de sistemas electrónicos e/ou informáticos. Neste contexto, pretende-se desenvolver um estetoscópio digital multicanal com capacidade de ligação à Internet. Desta forma, pretendemos demonstrar a viabilidade da aquisição, com elevada qualidade, de sons cardíacos e posterior transmissão via Internet. O *hardware* desenvolvido tem como principal componente um DSP (microcontrolador especializado em processamento digital de sinais). Com a utilização de um DSP pretende-se obter maior flexibilidade e fiabilidade no processamento dos sons cardíacos tendo em vista a obtenção de sinais de áudio de elevada qualidade. Uma vez que não existem testes padrão para avaliar a qualidade dos estetoscópios [2], os testes realizados focaram-se na parte eléctrica do dispositivo deixando para trabalho futuro a sua caracterização como um todo. Neste artigo descreve-se o *hardware* de aquisição e processamento dos sons cardíacos desenvolvido, bem como a caracterização eléctrica do mesmo através de uma série de testes normalmente utilizados na avaliação de equipamentos de áudio.

### 1. INTRODUCTION

A significant number of people from rural and suburban areas do not have access to optimal medical care due to lack of medical specialists. This happens because medical specialists choose to work in large urban centers

where the majority of the population is settled. With the spread of Internet access, web-based medical tools and services have been growing popularity within the medical community and, in many cases, Telemedicine has been seen as the best solution to minimize this problem [2]. Telemedicine based auxiliary diagnosis

tools can provide quick and efficient information about the health condition of a patient, in particular regarding heart diseases. Real-time telemonitoring of vital signs can be used in emergency scenarios to provide more and better information to support medical decisions [3].

The first medical tool used by medical students and one of the most used in the World, especially in the poorest regions, is the stethoscope [2]. The analysis of heart (and pulmonary) sounds gives to experienced physicians valuable information about the health condition of a patient [3]. However, usage in real-time scenarios is a difficult and challenging task due to the real-time connectivity, transmission speed and sound quality [2].

This work describes the development of a multi-channel digital stethoscope that includes Internet connection capabilities for real-time patient telemonitoring. Our goal is to develop a system that can be used by an expert physician to monitor one patient at a distant location.

This work is a proof-of-concept prototype developed as a joint project within the courses of “Sensors and Instrumentation” and “Digital Systems and Microcontrollers II” (“Sensores e Instrumentação” e Sistemas Digitais e Microcontroladores II) of the graduation in Electronic and Computer Networks, School of Technology and Management (Escola Superior de Tecnologia e Gestão – ESTG), Polytechnic Institute of Viana do Castelo (Instituto Politécnico de Viana do Castelo – IPVC).

## 2. ACOUSTIC STETHOSCOPE

Taking a look into an acoustic stethoscope will give a basic idea about the technical specifications and aspects for the digital stethoscope. Acoustic stethoscopes are composed of a chest piece connected by hollow tubing to two earpieces. The chest piece typically has two different sides, a bell and a diaphragm. The bell side is in the shape of a hollow cup. When placed on the patient, the vibration of the skin is transmitted as sound waves through the tubing to the earpieces. The bell is used to listen to low-frequency sounds such as those produced by the heart. The diaphragm side of the chest piece is usually a plastic disc stretched over a hollow cup. Sound waves from the body make the diaphragm vibrate, sending acoustic pressure waves through the tubing to the earpieces. The diaphragm is used to listen to high-frequency sounds, such as those produced by the lungs. The quality of an acoustic stethoscope is greatly affected by the quality of its chest piece. It was not intended in this paper to focus the work on studying the mechanical parts of the stethoscope, but mainly the chest piece [4] [5] [6].

This work describes only the stethoscope developed from the audio signal perspective, i.e., after the sound waves acquisition by the microphone. The position of the microphone placed inside the chest piece has not been studied in this work, since it requires a dedicated study in order to support which position should be the best to place the microphone inside. Having this in mind, and

considering that we do not have the technical knowledge necessary to design an improved chest piece, we decided to make only the electrical characterization of this stethoscope prototype.

## 3. MULTI-CHANNEL STETHOSCOPE ARCHITECTURE

The multi-channel digital stethoscope architecture is presented in Fig. 1. The acquisition front-end is responsible for the heart sounds acquisition, through active microphones followed by filtering, analog-to-digital conversion and channel equalization. A DSP is used to do channel equalization, which permits to customize the stethoscope frequency response. Different frequency responses can be programmed into the DSP, depending on the desired clinic speciality. The Micro Controller Unit (MCU) handles Ethernet communications and other system control functions, such as, bank-filter selection.

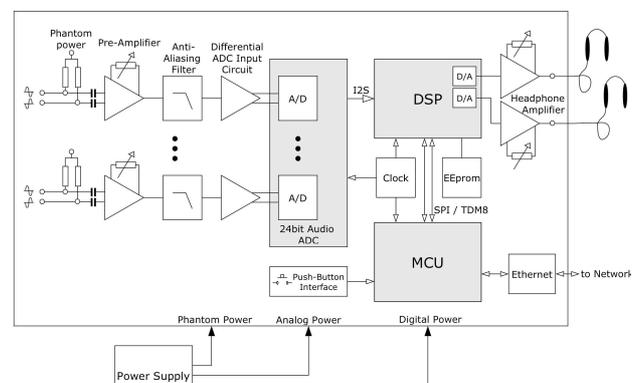


Fig. 1: Digital multi-channel stethoscope architecture.

### 3.1. Signal Acquisition Stage

A Panasonic WM-61A Omni-directional electret condenser microphone was used due its high linearity of  $\pm 1\text{dB}$  for frequencies from 20Hz to 5kHz and  $+1/-3\text{dB}$  for 5kHz to 20kHz, low noise floor and high sensibility of  $-35\pm 4\text{dB}$  ( $0\text{db} = 1\text{V/pa}$ , 1kHz). It will be built-in the chest piece to capture the acoustic pressure waves. The performance of the WM-61A is excellent [7], but it requires further signal processing to conform to phantom-powered-microphone standards. Sound pressure moves a diaphragm, producing variations in its capacitance. This action produces an ac-output voltage with extremely high impedance [7]. The electric signal produced by the WM-61A, is a very weak signal, in the order of tens of mV.

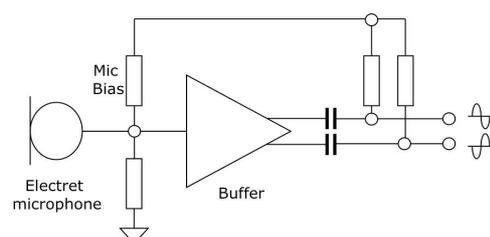


Fig. 2: Signal acquisition state with active microphone.

An integrated circuit with dual ultra-low noise and low distortion op-amp will make use of one op-amp as simple voltage buffer that provides low-impedance drive for one output and the other op-amp will act as a unity-gain inverter that derives its drive from the output of the first op-amp, generating a phase inverted signal. The output of this active microphone is a low-impedance differential signal. The amplifier outputs, see Fig. 2, use ac coupling in the active microphone output terminals, to block the dc phantom-power voltage, on the audio lines. Phantom-powered microphones derive power for their active circuitry from the receiving-end circuit through the same leads that transmit the audio signal. A balanced microphone cable will be used between the active microphone chest piece and the receiving-end amplifier.

### 3.1.1. Pre-Amplifier and Filtering

The receiving-end for the active microphones provides phantom power and takes advantage of THAT 1510, an ultralow-noise instrumentation amplifier, from THAT Corporation with three internal op-amps. The THAT 1510 improves on existing integrated microphone pre-amps by offering lower noise at low gains, wider bandwidth, higher slew rate, lower distortion, lower supply current and provides excellent CMRR (common-mode-rejection) properties [8]. The high CMRR rejects noise and power-line hum that appear equally in both signal lines. This instrumentation amplifier is used as an audio pre-amplifier and its gain is adjusted with a trimmer from 20 to 60 dB, see Fig. 3.

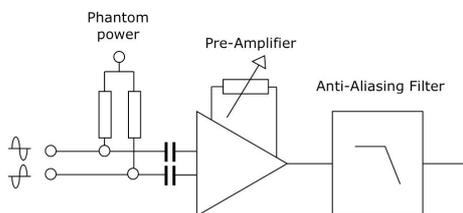


Fig. 3: Audio pre-amplifier and filtering stage.

The output signal from the audio pre-amplifier is then filtered by an active anti-aliasing filter formed by a variable Sallen and Key low pass filter design, with cut-off frequencies between 3,1 and 42 kHz. The anti-aliasing filter output is then sampled by the Analog Devices AD1974 ADC. This audio ADC has 4-channels and operates with 24 bits sampling depth and must be driven from a differential signal source for best performance, see Fig. 4.

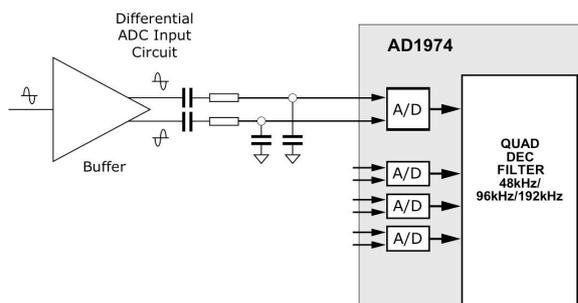


Fig. 4: AD1974 differential input conversion.

The input pins of the AD1974 connect to internal switched capacitors. To isolate the external driving op-amp from the glitches caused by the internal switched capacitors, each input pin is isolated by using a series connected resistor together with a 1nF capacitor connected from each input to ground. This capacitor is a high quality ceramic NPO [9]. Some care was taken to choose high quality capacitors and high precision metal film resistors in all audio paths.

### 3.2. DSP Unit

The DSP Unit used was the ADAU1701 SigmaDSP® from Analog Devices. This unit is a complete single-chip audio system, with a built-in audio DSP, built in DACs, and MCU-like control interfaces.

Signal processing capabilities includes, equalization, audio enhancement, among others, and can be used to improve limitations of real-world audio signals, providing improvements in the perceived audio [10].

The ADAU1701 can be programmed with the Analog Devices SigmaStudio™ software, which allows us to graphically configure a custom signal processing workflow using blocks such as filters, level controls or GPIO interface controls. Compiled code is generated by the SigmaStudio™, and can be loaded on power-up either from a serial EEPROM through a self-boot mechanism or from an external MCU. On power-down, the current state of the memory of the ADAU1701 is written back to the EEPROM, to be recalled the next time the chip is started [11].

Channel equalization was made using three-second order IIR Filters that can be found under the General Purpose Filter Library in SigmaStudio™ [10], see Fig. 5.

The stethoscope channel equalization used in the testes, follows a simple topology, based on these specifications:

- Should attenuate 8 dBs, the 50 Hz line noise.
- Should boost 3 dBs @ 25 Hz.
- Should boost 2.5 dBs @ 1000 Hz.

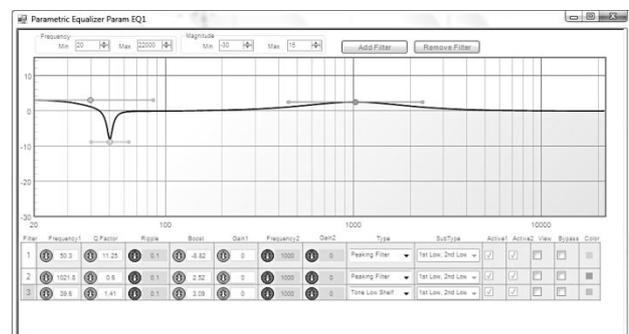


Fig. 5: SigmaStudio™ GUI - Stethoscope Channel Equalization Filter Design.

### 3.3. Headphone Output

To implement the Headphone output, see Fig. 6, the processed audio stream is converted back into an

analogue audio signal for real-time listening. The ADAU1701 provides four high quality on-board Delta-Sigma DACs. Each DAC channel is followed by a low-pass filter that reconstructs the signal existent in the DAC output. Finally, the audio signal is amplified by a high-output-current op-amp, the NJM4556AD, to drive the headphone speakers.

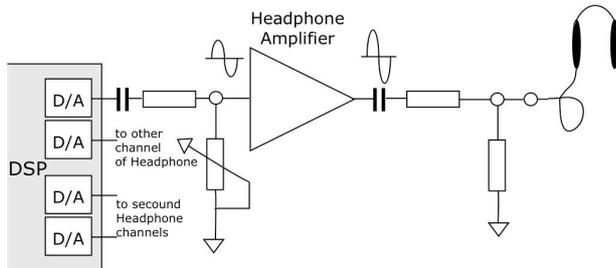


Fig. 6: Headphone output stage.

### 3.4. Micro Controller Unit

The MCU chosen was the Microchip™ PIC32MX785L which has built-in Ethernet capabilities. The MCU controls all the on-board peripherals, and makes the “bridge” between the stethoscope and the exterior world. Control data communication between the MCU and the ADAU1701 is made through a serial SPI port. Audio data communication between MCU and the ADAU1701 is performed by a serial I2S port, running in TDM-8 Channel mode.

Due to the high rate audio data transmitted between the stethoscope and a possible client application running in a PC in the local area network (LAN), and taking into account the common use of Ethernet today, the communication protocol chosen in the Ethernet-based communications was the User Datagram Protocol (UDP). The advantages of using UDP are its simple message-based, connectionless protocol and it does not set up a dedicated end-to-end connection. Communication is achieved by transmitting information in one direction from source to destination without verifying the readiness or state of the receiver, making it lightweight [12].

### 4. AUDIO TESTS

Audio tests were performed only for the electrical part of the stethoscope. The characterization of the mechanical parts has been left for future work, given the difficulties normally encountered in the characterization of the acoustic parts of stethoscopes. The equipment used for the tests was the Portable One, made by the well-known Audio Precision Inc. This equipment allows performing standard tests, commonly used in industry, for quality certification of audio equipment. Figure 7 shows the prototype under testing.

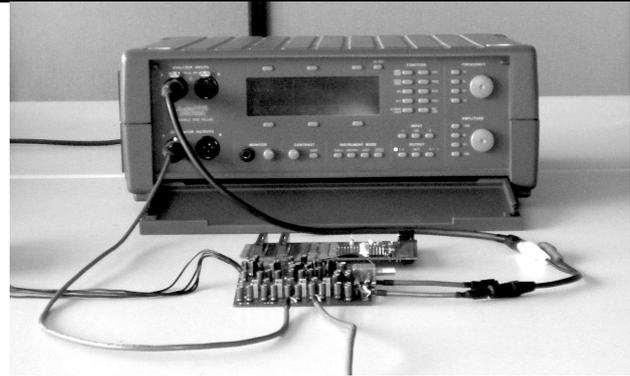


Fig. 7: Audio tests performed with the Portable One.

The experimental results were grouped in Tab. 1. The input signal used was a sinusoidal function with 25 mVpp and 1 kHz frequency.

### 5. RESULTS

The results were grouped into table 1. The input signal used under testing, was a sinusoidal function, with 25 mV peak-to-peak and 1 kHz frequency.

Parameter	Value
SNR	78.70 dB
THD+N	0.0251 %
Load	1990.0 Ω

Tab. 1: Experimental results.

We also carried out a sweep of frequencies with the Portable One to obtain the stethoscope frequency response. The figure below shows the result obtained.

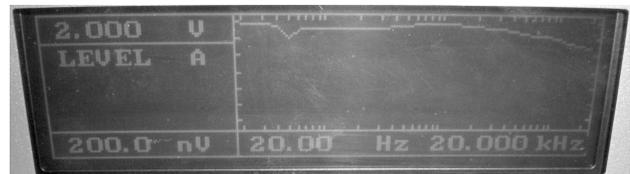


Fig. 8: Frequency response obtained with the Portable One.

### 6. CONCLUSIONS

As already stated, our final goal was to develop a proof-of-concept prototype of a multi-channel digital stethoscope.

The stethoscope channel equalization proved to be a major feature. With this feature, it is possible to include different frequency responses in the stethoscope memory and customize the device for different clinical specialities.

The developed stethoscope was tested using one of the most reliable equipment in the Audio industry, the Portable One from Audio Precision Inc. A high value for the Signal to Noise Ratio (SNR=78.7dB) was achieved, and a low Total Harmonic Distortion plus Noise (THD+N=0.0251%) was measured. These results show that it is possible to build low-cost digital stethoscopes with reasonable quality and some advanced features.

## 7. FUTURE WORK

As future work we intend to develop and implement algorithms to extract valuable information from heart sounds in order to detect abnormal functioning of the heart. Finally, the device should be able to collect ECG signals synchronized with the heart sounds. Regarding the communications, the device must evolve to wireless.

## 8. ACKNOWLEDGMENTS

We would like to thank the Department of Electronics, Telecommunications and Informatics of the University of Aveiro, in the person of Professor José Neto Vieira, the access to the test equipment used to evaluate this project.

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