A Low-cost 3-D Printed Stethoscope Connected to a Smartphone*

Carlos Aguilera-Astudillo, Marx Chavez-Campos, Alan Gonzalez-Suarez, and Jose L. Garcia-Cordero

***Abstract*— We demonstrate the fabrication of a digital stethoscope using a 3D printer and commercial off-the-shelf electronics. A chestpiece consists of an electret microphone embedded into the drum of a 3D printed chestpiece. An electronic dongle amplifies the signal from the microphone and reduces any external noise. It also adjusts the signal to the voltages accepted by the smartphones headset jack. A graphical user interface programmed in Android displays the signals processed by the dongle. The application also saves the processed signal and sends it to a physician.**

Keywords; Dongle; Digital stethoscope; 3-D printed chestpiece; Smartphone app.

I. Introduction

A. Mobile Telemedicine and patient monitoring.

In developing countries, as well as poorer areas of developed countries, mobile telemedicine has become an affordable alternative to close the gaps that exist in the quality of health care. Mobile telemedicine can be defined as the communication or consultation between health professionals and their patients using data or media acquired with a mobile device. Additionally, in the context of mobile telemedicine, patient monitoring is defined as using technology to manage, monitor and treat a patient´s illness from a distance with the help of sensors linked to mobile phones [1]. The sensors comprise wearable and portable or implantable systems which are able to monitor vital signs such as blood pressure, heart rate, or blood sugar. These signals are then analyzed by an application in the smartphone, and finally, transmitted over the mobile wireless network to a doctor.

A variety of peripherals or dongles can be plugged into different ports already included in smartphones (*e.g.* microUSB, headset jack). The smartphones can be used to power and control these peripherals and also analyze the collected data. Some representative applications include a microfluidic dongle to diagnose HIV [2], a pulse oximeter using a smartphone camera and its built-in LED [3], blood pressure measurements using both the camera and headphone port [4], and acquisition of ECG signals through an audio DAQ card [5].

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B. Auscultation and use of the stethoscope

When a patient goes to a medical check-up, the first physical examination the physician performs is called auscultation. This technique provides the doctor with some clues about how the heart from a patient sounds and works. The doctors may listen to the sounds emitted by the heart and lungs with the aid of a stethoscope and can evaluate, for instance, the heart and valve function, or the heart´s rate and rhythm by listening to a "lub dub" noise, which is a simple onomatopoeic representation of the sound [6-7].

Research has shown that current characteristics of smartphones are sufficient for powering and communicating with external devices. Also, applications can be developed in different programming languages with the aid of manuals that document their mechanical and electrical characteristics (*e.g.* the headset port) [8]. Taking advantage of such characteristics has permitted the development of applications where the smartphone is used to monitor physiological signs, including breathing and heart sounds [9].

Other groups have developed digital stethoscopes connected to smartphones [10-11]. In one case, the smartphone's "hands-free" microphone was embedded into a standard stethoscope; this digital stethoscope was used to recognize lung sounds [10]. In a different case, a smartphone was interfaced with a commercial digital stetoschope (ThinkLabs One, USA) [11]. And companies, such as 3M and Cardionics, already commercialize digital stethoscope at prices starting from USD$335 (plus shipping and import taxes), amounts that, in our perspective, are prohibitively expensive for low-income countries. In this paper we report the design, fabrication, and testing of a low-cost 3D-printed electronic chestpiece. Off-the-shelf electronics and an electret microphone are embedded into a chestpiece. We used our digital stethoscope with four male patients and demonstrate that it can distinguish the first and second heart sounds.

II. Methods

A. Description of the system.

The 3D-printed physical chest piece, the dongle and the smartphone connected through a TRRS wire are shown in **Figure 1**. A heart sound signal is displayed on the phone's screen with an amplification of 40dB.

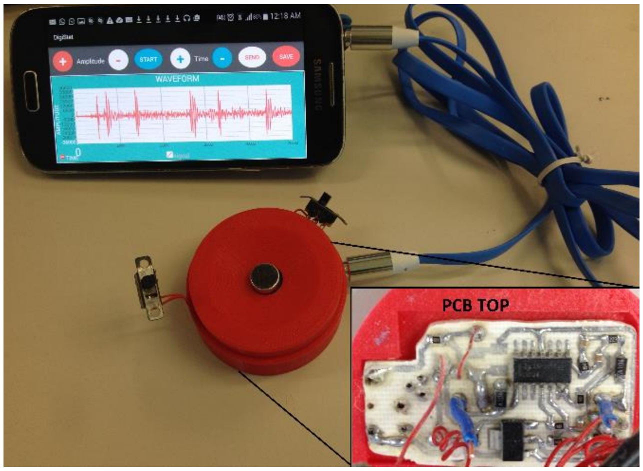

Figure 1. Integrated digital stethoscope system connected to a smartphone.

The purpose of the start button is to record the sounds when the dongle is connected and the chest piece is in position to auscultate the sounds from the heart. The buttons of amplitude and time are unavailable before the acquisition starts. When the signal is ready, the buttons of save and send will be unlocked, so that the user can save the information.

The system concept, shown in **Figure 2**, consists of three main blocks: a dongle, a 3D-printed chestpiece, and a smartphone application. The system could be operated either by a doctor, a nurse, or by the patient. The dongle is a battery-operated electronic device that is plugged into the smartphone on one side, and on the opposite side is connected to the 3-D printed chest piece. The dongle consists essentially of an electronic circuit designed to condition the signal received from the microphone located in the chestpiece.

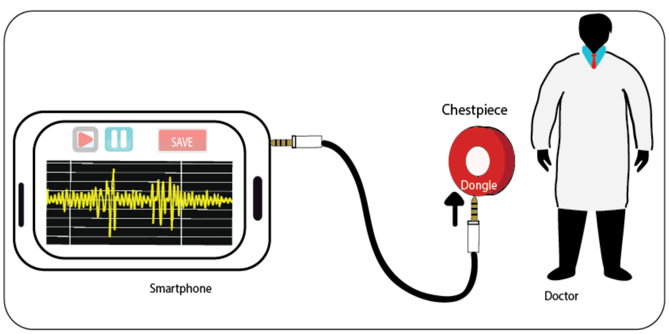

Figure 2. System concept. A smartphone able to acquire, display and save the heart sound information in order to be analyzed by a physician. The acquisition is performed through a dongle and a 3-D printed chestpiece connected to the smartphone.

The chestpiece usually consists of two parts connected by a drum that can be placed against the patient: the bell and the diaphragm. The bell transmits lower frequency sounds, while the diaphragm transmits higher frequency sounds. When the bell or diaphragm is placed on the patient, the vibrations of the skin or body, respectively, produce acoustic pressure waves that travel to the listener's ear [12]. Most stethoscope chestpieces are made from aluminum or steel, which automatically renders them expensive. 3D printing is a technology that permits creating prototypes in a matter of minutes at a very low cost. It's a technology that is becoming increasingly affordable and it is expected that in the future a large percentage of households could own one. For example, Mattel just released its first printer for creating toys.

We designed and fabricated a 3-D printed chest piece using a Makerbot Replicator 2 (USA). Our bell consists of a microphone attached to the chestpiece. The cost of this PLA-made chestpiece is less than a dollar, lower than the cost of a regular metallic stethoscope and even lower than commercial digital stethoscopes [13].

Noteworthy is the use of the TRRS connector´s ability to communicate with both the smartphone and the dongle due to the versatility it provides. The TRRS is an open and simple interface which has become a standard in most smartphones on the market. This connector also makes it possible to split the audio signal so that it can be transmitted to the earphones at the same time as it is being recorded.

B. Design of the dongle.

A schematic of the parts of the dongle is shown **in Figure 3.a**. It consists of 4 essential blocks: a microphone, an amplification stage, a filter stage, and a signal conditioning stage. All these stages were implemented on a single printed circuit board and integrated into the 3-D printed chestpiece, with an output able to be connected directly to the smartphone through a TRRS wire.

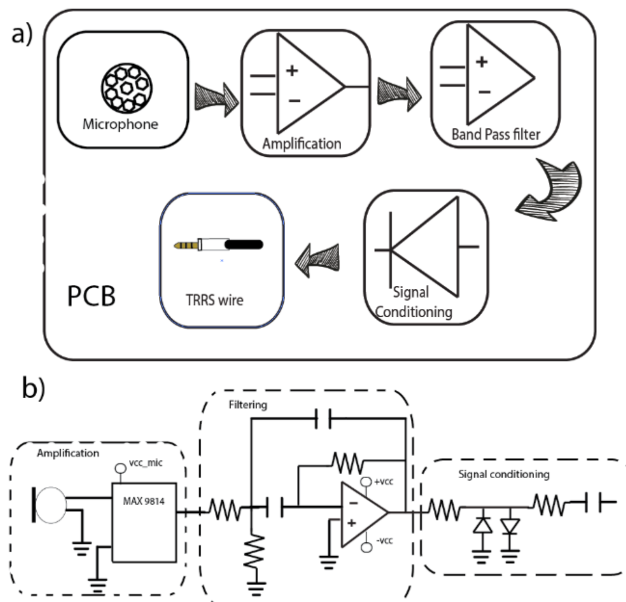

Figure 3. Block diagrams of the dongle. A) There are five essential blocks within the dongle. The microphone, the amplification stage, a band pass filter, and signal conditioning with an output that can be connected to the smartphone through a TRRS wire. B) The signal from the microphone is biased and amplified with the MAX9814. The signal is filtered and conditioned before getting into the smartphone.

Most smartphone headsets come with microphones which perform well for transmitting or receiving vocal sounds. Initially, we extracted a microphone from a headset (6mm diameter). First, we characterized its performance for low-frequencies by generating tones with code programmed in Scilab (opensource) and checking that the output of the microphone matched the incoming signal. The results showed that the electret microphone signals where in a range of tens of millivolts. Next, we tested the microphone for acquiring heart sounds but it was difficult to manipulate because of its small size. In addition, this microphone is not suited for recording sounds generated in the chest. Finally, we tested a microphone (CMA-4544PF-W, CUI Inc) with a diameter of 9.7 mm, which was easier to handle and fit into the chestpiece. The dongle replicates the acoustical and electronic functions of a typical digital stethoscope. A small battery powers the components in the dongle. The dongle was designed with the microphone situated as close as possible from the top of the chestpiece, as already described by other authors [14].

The amplification stage consists of adjusting the signals from the electret to the smartphone microphone jack voltage levels. The signal from the microphone is fed into a microphone amplifier with automatic gain control and low-noise bias (MAX9814, Maxim Integrated, USA). This automatic gain can be adjusted by a mechanically-controlled switch on the dongle. There are three available gains (40dB, 50dB and 60dB) which can be selected depending on how loud the physician wants to listen to the heart sounds.

Doctors and medical staff in developing countries deal with large numbers of people in hospitals, medical centers, or emergency rooms. For these doctors, it is sometimes difficult to listen clearly to the sounds of the body using normal stethoscopes. In addition, the lack of dedicated rooms for personalized attention or to reduce environmental noise represents a problem when using stethoscopes. This excess of noise may cause a misdiagnosis since the results of the examination could cause confusion about what the doctor is listening to through the stethoscope. Therefore, having a design that minimizes any noise and creates better conditions for the doctor to listen to the heart is essential in any stethoscope.

Some heart sounds are found in a 20-150 Hz range. We designed an electronic band pass filter with a center frequency of 30 Hz with a range from 25 and 65 Hz. The center frequency can be shifted up to 150 Hz when required. The band pass filter response is shown in **Figure 4**. Finally, a signal conditioning stage includes a clipper to avoid having voltage spikes and damaging the device.

C. Design of the application in a smartphone.

The application was developed in Android OS KitKat (4.4.2) in a Samsung Galaxy Mini S4. The top part of the graphical user interface, as shown **in Figure 5**, consists of a couple of input boxes to capture the user's name and e-mail. This step is important to control the results and to send the information after the examination is performed.

To develop the application we selected an audio capture API from Java called Audio Record class. This API allows access to uncompressed raw data. The main parameter to choose before recording audio was sample rate. The first sample rate tested was 8000 Hz. Since a higher sample rate translates into a higher resolution, we also tested it with 11025 Hz, 22050 Hz and 44100 Hz with similar results. However, a sample rate of 44100Hz is currently the only rate that is guaranteed to work across all devices, whereas higher frequency rates such as 22050, 16000, and 11025 might work only on some devices [15].

Once the sound has been acquired, the smartphone interprets the data as PCM (Pulse Code Modulation) digital data. We designed a graphical user interface to plot this audio raw data. The interface consists of 4 buttons that allow the user to scale the amplitude and time for an easier visualization of the signal. We considered that the interface may be used not only for disease diagnosis but also as an educational tool. For this reason, the user can save the displayed signal in two formats: as a csv file and as a WAV format. We are currently adding functionality to this interface to include an algorithm that analyzes the signals.

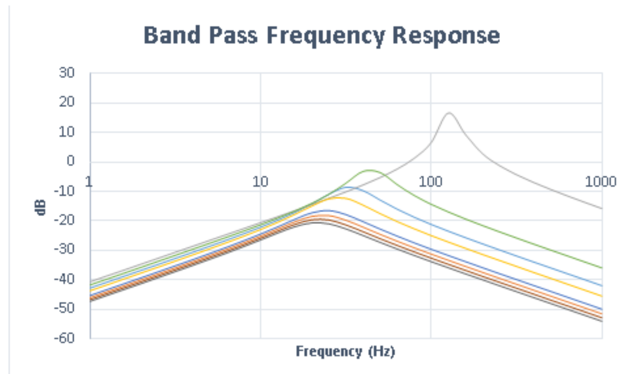

Figure 4. Optimization of the band pass filter frequency response.

Figure 5. Graphical user interface. The top part shows the initial screen with captured boxes for the patient´s name and e-mail. The bottom parts shows the heart sounds displayed on the screen of the phone.

III. RESULTS

Examples of data acquired with the microphone are shown in **Figure 6**. The top graph, Fig. 6.a., data for heart sounds acquired directly using an electret microphone. This signal is mounted on a DC level because the microphone is biased by the MAX9814 IC. The bottom graph shows a signal acquired with the same electret microphone but filtered through our dongle. This signal is referenced to zero due to the AC coupling from the filter capacitor.

We tested our dongle with four male patients sitting down. The chestpiece was set with a gain of 40 dB and placed on the right-hand side of chest. Results from this experiment are shown in **Figure 6.b.** In general, our dongle easily detected the first (S1) and second (S2) heart sounds for three of the patients auscultated. The signal from the fourth patient had higher noise than the rest of the patients. We are currently optimizing the band-pass filter to reduce the noise and improving the design of the chest-piece.

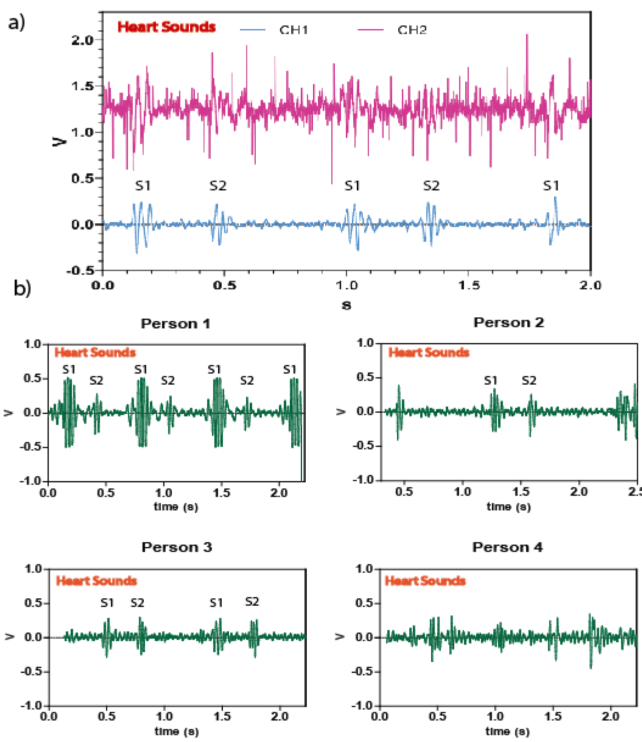

Figure 6. Heart sound signal before filtering (pink) and after filtering (blue) with our dongle (a). Heart sound signals for four male patients are displayed in (b).

IV. DISCUSSION AND CONCLUSION

We created a digital stethoscope with the help of a 3-D printed chestpiece together with off-the shelf electronics. Integrating an electret microphone into a plastic chestpiece and connecting it to a smartphone, makes this technology accessible and affordable to anyone with access to a 3D printer and a smartphone. Our stethoscope may help promote the use of stethoscopes in communities where there is no access to doctors or nurses and in emergency situations. The aim of our system is to let anyone perform preventive self-care with the help of devices like the one we propose and relay the data to a doctor's office, a hospital or indeed anywhere for analysis. Also, the signals can be stored so that it can be used as reference in the future.

We are currently working on improving our system, playing the signal in the speaker phone, controlling the amplification of the signal, and implementing a signal processing algorithm. In addition, we plan to test the stethoscope in real situations; receiving feedback from doctors, cardiologists, and anesthesiologists would help us improve our device. Furthermore, we plan to create a database with the sounds of healthy persons as well as those suffering from a heart condition so that the doctor and students can familiarize themselves with the different types of signals.

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