ELECTRONIC STETHOSCOPE ARRAY

By

Robin GUIGNY

Fatima Zohra HASNAOUI

Final Report for ECE 445, Senior Design, Spring 2016

TA:Cara Yang

5 May 2016

Project No. 70

Abstract

The purpose of this document is to present our design of an electronic stethoscope. The device consists in an acquisition and signal treatment part that sends lung sounds to a computer. Then, the software we programmed will allow a doctor to set his diagnosis.

Contents

1. Introduction

Two out of five patients are misdiagnosed or under-diagnosed every year with the use of a traditional stethoscope. It only provides a qualitative assessment of the lung activity of a patient. Indeed, doctors only listen to sounds produced by the patient breathing and establish their diagnosis based on their listening.

Our aim is to create a self-contained electronic stethoscope that record and amplify these signals using a microphone chip in order to assess the lung activity. The microphone chip will be attached in between the chest piece and the tubing, capturing the vibrations that the diaphragm produces. A software we designed will then process these signals, analyzing both the frequencies and the amplitude of the sounds. The final data and preliminary diagnosis will be given in an easy-to-read output for the doctor (figure 1).

Current electronic stethoscopes only contain a single sensor that has the capability to amplify lung activity and reduce outside noise. Our idea is to both capture and analyze the signal across the lung and provide details about the symptoms.

Thus, the project can be divided in two parts: the hardware design, and the software implementation.

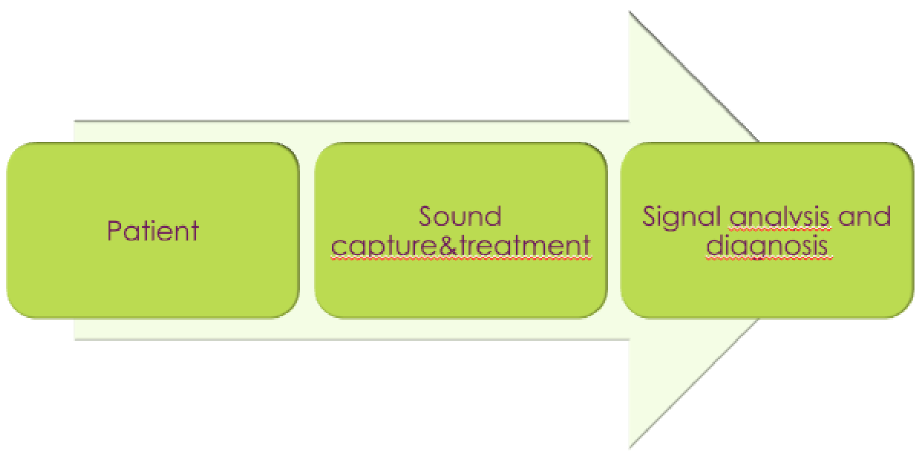

Figure 1- Project overview

2. Design Procedure

Our final design consists of six modules. The acquisition unit records the lung sounds, a filter attenuates unwanted frequencies and feed the signal to both a headphone amplifier and a Bluetooth module. The software processes the signal sent by the BT module and gives a preliminary diagnosis. The power unit supplies all the other modules. Figure 2 shows an overview of the design.

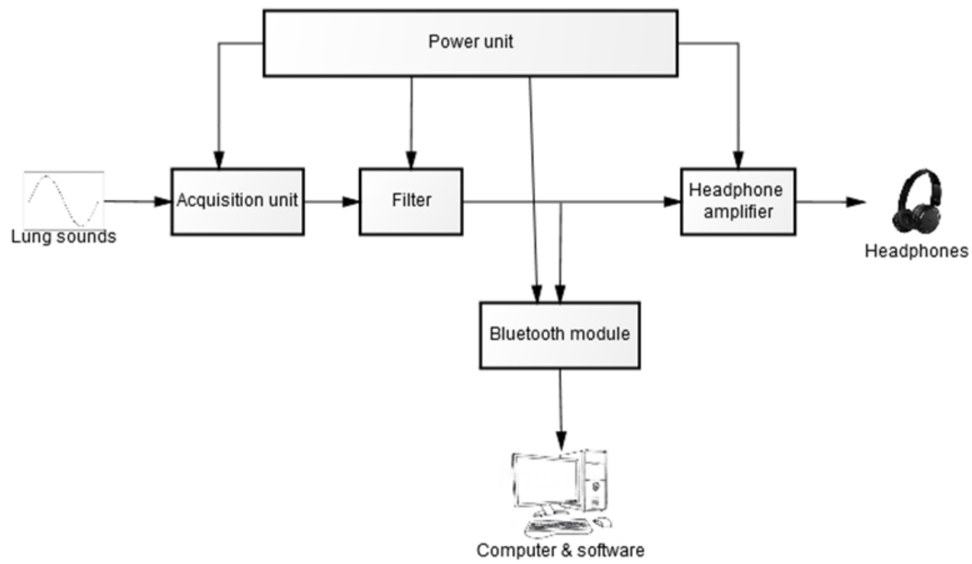

Figure 2- Block diagram

2.1 Microphone

The first component of our design is the microphone. In order to choose the appropriate one, we compared three microphones after we stated the criteria that seemed important to us.

The microphone has to:

- Have a good sensitivity to detect even the smallest breathing sounds.
- Respond to low frequencies sounds.
- Be affordable to unsure a low cost final design.
- Be relatively not affected by electronic interferences.

The three microphones we compared are an electret condenser microphone, a Micro Electrical Mechanical System (MEMS) microphone and a fiber optic microphone. We looked at their performance using online documentation to make the right choice.

Table 1 – Microphone comparison

	Electret condenser	MEMS	Fiber Optic [2]
Sensitivity [1]	Between -46dBV and -35dbV	Between -46dBV and -35dbV	
Frequency response	>10Hz	>100Hz	>20Hz
Cost	≈1$	≈1$	>400$
Interferences	Magnetic interferences	Magnetic interferences	None

The fiber optic is the best microphone as it has a very good frequency response, sensitivity and is not affected by magnetic fields in any way. However, it is too expensive for us to include it in our design. The electret condenser seems to be the most reasonable choice. The MEMS microphone cannot capture frequencies below 100Hz when some lung sounds can have frequencies as low as 50Hz. There are interferences in both the MEMS and electret microphone designs, which should be later on reduced with a proper packaging.

Our final choice was to use an electret microphone.

2.2 Filter

The filter is necessary to isolate the lung sound we want to focus on, after having recorded it with the microphone. More than recovering the entire lung sound range of frequencies - between 50Hz and 2500Hz - it has to make sure we get rid of heartbeat sounds (under 50Hz) and trachea noises (above 6000Hz)[3]. Thus, we require a filter with high attenuation in the stop bands, and a flat pass-band (see Requirements and Verification table in Appendix A). To allow any further modification, we also wanted an easy circuit design. Considering all these requirements, we picked a Butterworth bandpass filter with a Sallen-Key design. The choice of the order was figured out experimentally. Indeed, we first tried with a second order bandpass filter, but the attenuation we had was inconsistent with our expectations and needs. In the end, a third order filter has shown to be satisfactory.

A Sallen-Key design was the most appropriate, given how easy it is to modify and adjust. We then had to determine our components' values.

2.3 Headphone amplifier

The signal coming out of the filter needs to be fed to headphones. The purpose of the headphone amplifier is to obtain enough power to drive the lowest impedance headphones. For this module, even simple designs can be satisfying as they can be improved in terms of noise by adding simple resistors and capacitors.

The choice of the amplifier is obviously related to the sensitivity of both the microphone and the earphones.

The earphones we used for our design are the Panasonic RP-HJE120-V. The impedance we measured was 9Ω, and the datasheet gives a sensitivity of 96 dBSPL/mW.

We'll try and obtain the necessary amplification using a CMoy amplifier design detailed later on in this paper. This design is very modular, which will allow us to modify the values of the gain and act on the noise regulation more easily. Moreover, a lot of operational amplifier would be able to work in this design.

This design has also proved to be able to drive a good range of impedances (8Ω to hundreds of ohms), which will allow good performances with all kinds of headphones.

2.4 Bluetooth module

The lung sounds that have been acquired and filtered need to be sent to the computer. We'll be using a Bluetooth module for that purpose. We wanted our module to have an analog input so it could directly convert and send the data to the software. The range and speed of the module wasn't a concern. Indeed, the device is to be used in a doctor's office next to a computer (distance of maximum 5 meters) and the acquisition doesn't need to be made in real time. Even if it takes a few minutes to process the signal, this is not a problem.

We chose to use the Numato's 8 channel GPIO BlueTooth module, which has analog inputs and easily passes the low requirements we had in terms of range and speed.

2.5 Power supply unit

The power supply unit is the part that will power every component of the hardware. We want the battery to last for about a month. Assuming a doctor uses the device for 30 minutes a day, 5 days a week, the device should be able to last 10 hours without changing the batteries. With such battery lifetime, there is no real need for a rechargeable battery.

The other modules need four different voltage levels to work properly: +9V and -9V for the operational amplifiers, +5V for the Bluetooth module and +3.0V for the microphone. We'll later describe our design for the power unit.

2.6 Software design

The software is in charge of visualizing and analyzing lung sounds sent by the hardware. The two main adventitious sounds that are linked with lung symptoms are wheezes and crackles, which features are recalled below.

Table 2- Lung sounds characteristics

Sounds	Max peak frequency [4],[5]	Waveform[5]	Duration[5]
Wheezes	400Hz	Sinusoid	>80 ms
Fine Crackle	650Hz	Dampened wave deflection	Around 5ms
Coarse Crackle	350Hz	Dampened wave deflection	Around 15 ms

The focus of the software is frequency recognition: since every sound has a specific maximum peak frequency, they should be distinguishable. However, the abnormal sounds are added to the normal breathing signal of the patient, so the software has to take the normal sound maximum peak frequency into account.

We implemented the software with Python language.

3 Design Details

3.1 Filter

We find the value of the filter's components by identifying the Q factor and the cutoff frequency in both the lowpass and highpass transfer functions. For example for the low-pass filter :

$$\frac{V_{out}}{V_{in}} = \frac{2\pi f_{c2}}{s + 2\pi f_{c2}} \frac{(2\pi f_{c2})^2}{s^2 + \frac{s}{Q} 2\pi f_{c2} + (2\pi f_{c2})^2} \qquad (1)$$

With $Q = \frac{1}{\sqrt{2}}$ and $f_{c2} = 2500Hz.$

We can fix the value of 2 capacitors before the identification.

We obtain the following values and schematics for the filter design (figure 3).

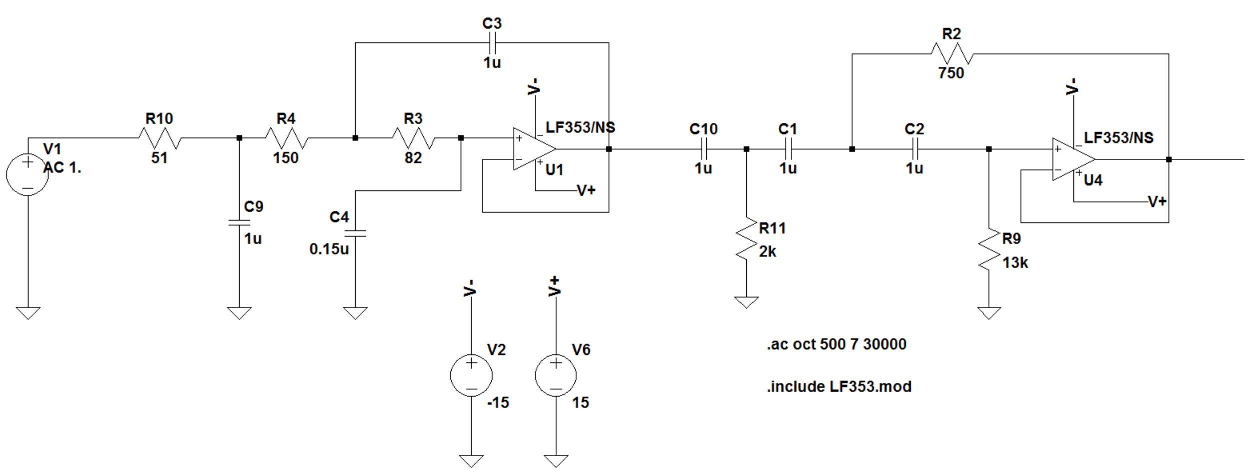

Figure 3-Butterworth filter circuit design

After that, we decided to simulate the transfer function of the filter with the software LTSpice. It gave us a satisfactory Bode diagram, where the band-pass is flat, and the attenuation in the stop bands is high.

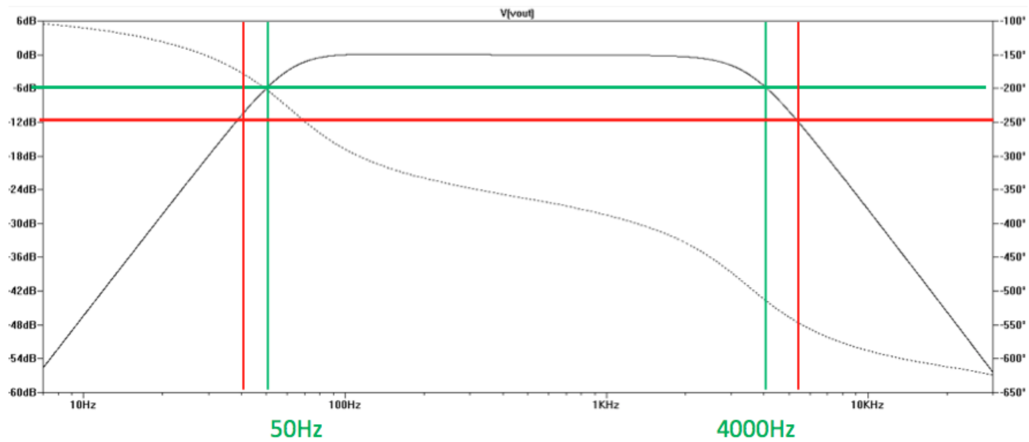

Figure 4-Simulated Bode diagram with LTSpice

3.2 Headphone amplifier

To allow a real-time assessment of lung activity, the device includes a headphone. The signal has to be amplified before going into the headphones.

We referred to the Sound Exposure Level table [6] to calculate the necessary power input of the earphones. We want the loudest lung sound that can be heard to be in the beginning of the “danger zone” i.e. to be tolerable for a few hours. This corresponds to about 93 dBSPL (the average sound level of heavy traffic) and 0.5mW for our earphones.

$$0.5mW = \frac{V_{min}^2}{R} \text{ with } R = 9\Omega \rightarrow V_{min} = 67mV \qquad (2)$$

By experimentally measuring signals coming out of the microphone, we figured amplifying the signal by 100 should provide the expected voltage for the loudest lung sounds. The design of the Cmoy amplifier [7].

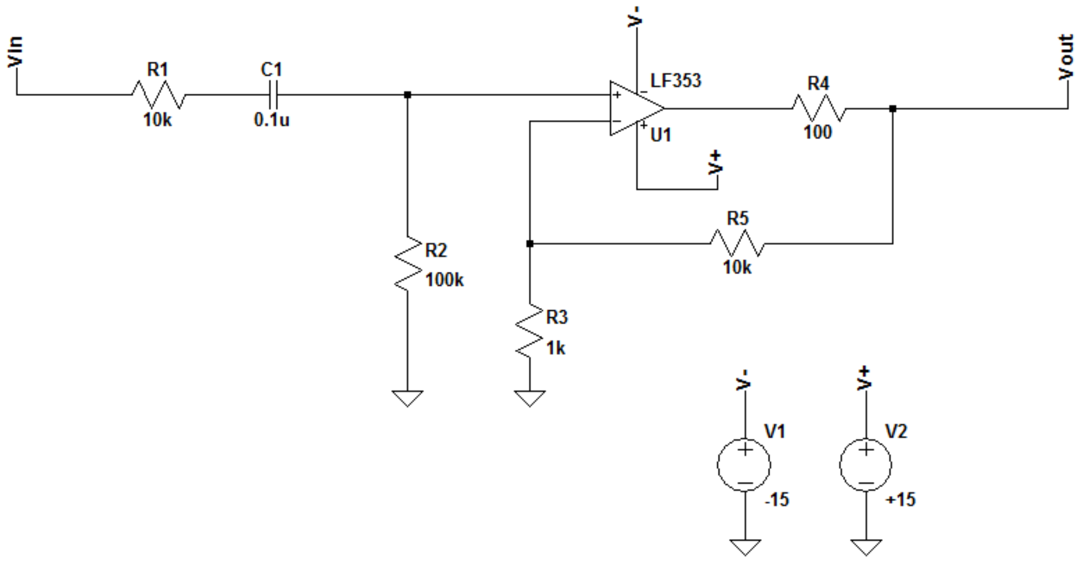

Figure 4- Cmoy headphone amplifier schematic

Note : the resistor R4 is there to attenuate noises and has to be chosen experimentally [7].

3.3 Power unit

We picked two alkaline battery of 9V each, and a coin cell battery of 3V for the microphone. A linear voltage regulator will be in charge of providing 5V input to the Bluetooth module.

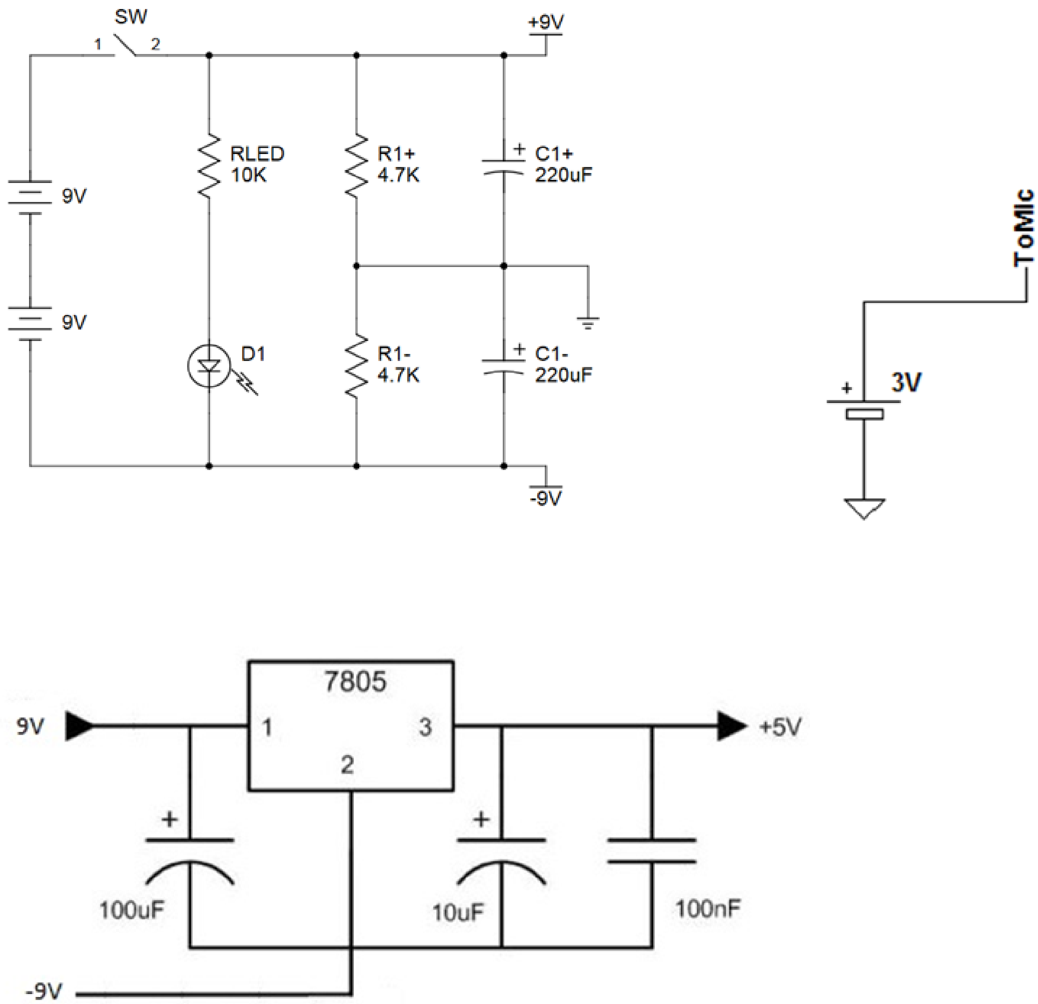

Figure 6 - Battery unit schematics

We used the -9V output as a reference for the 7805 voltage regulator because the middle rail of the two 9V batteries was unstable with this design. This, we learned afterwards, could have been prevented by modifying the design. This is also the reason why we had to consider using a cell-coin battery to power the microphone. Even if this design is far from optimal, the voltages it provides are accurate and we were able to use it effectively to power the other modules.

3.4 Software Flowchart

The software main purpose is to spot any irregular sound by analyzing the recording's maximum peak frequency. For that, the software has to compute the FFT on the sound, and then spot the maximum amplitude frequency. If it fits in the range of frequencies of an abnormal sound, it will detect it.

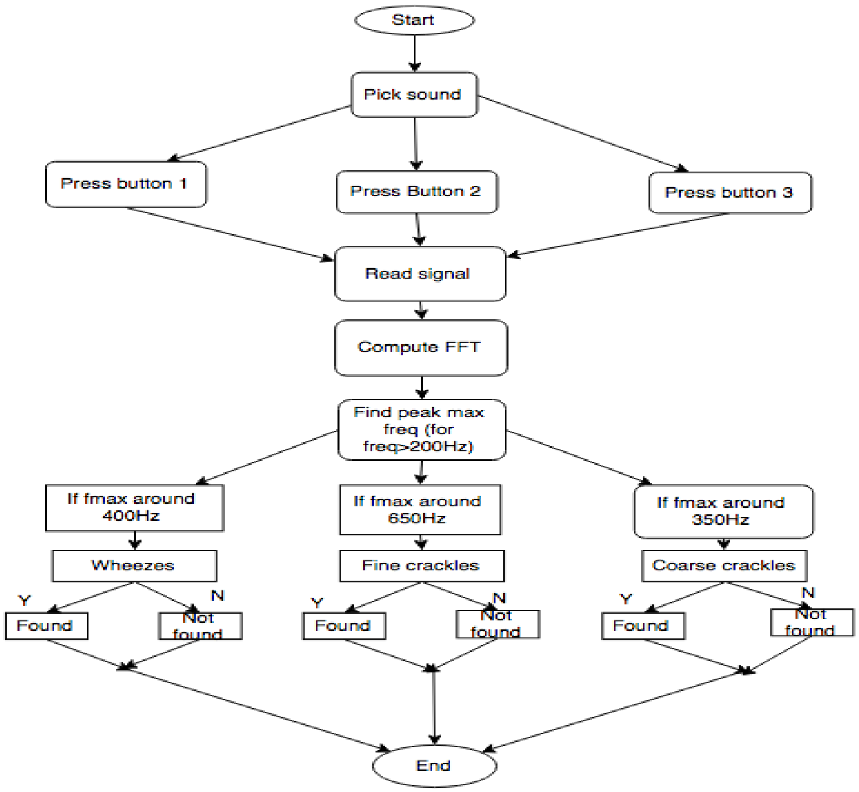

Figure 7 - Software flowchart

We want the software to have a short latency and a high success rate. We estimate that 2s to 10s latency is acceptable in order to allow the doctor to use the software to set his diagnosis during the consultation. Moreover, we want 95% of success rate, and leave 5% of flexibility for failure. The consequences of such failures are discussed in the ethics section of this paper.

4 Design Verification

4.1 Filter

To verify that the filter we designed fits the requirements we established, we measured the output for a 2.5 V input at different frequencies to obtain the actual Bode diagram (figure 8).

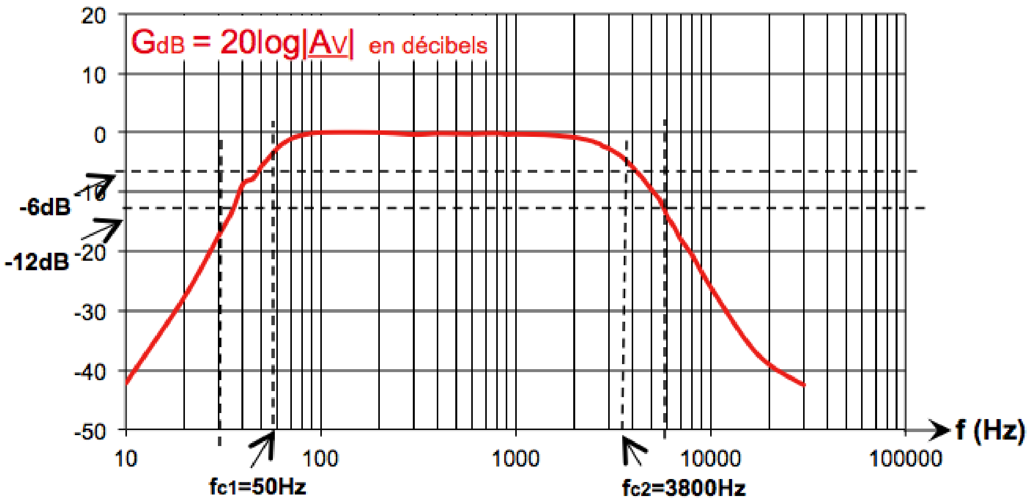

Figure 8 - Filter's experimental Bode diagram

The requirements we set for this filter (Appendix A) concern 4 different frequencies. The verifications for those requirements are highlighted in figure 9.

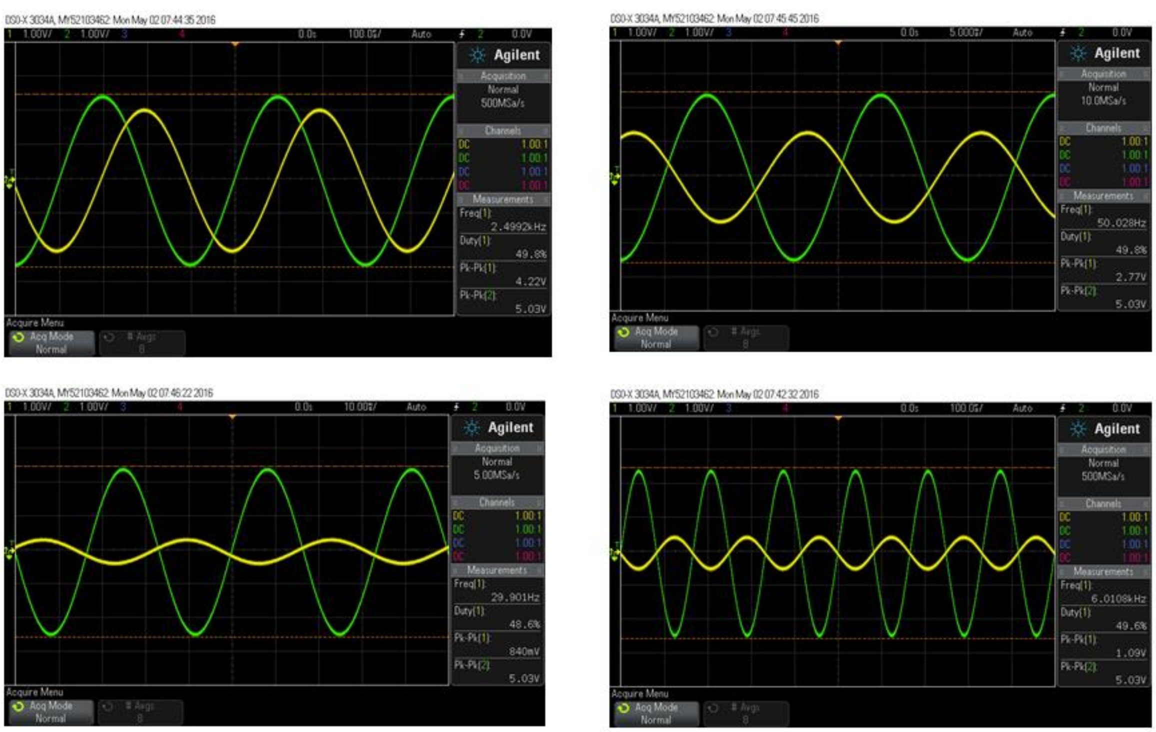

Figure 9 - Filter verifications

The phase shift that we can notice on those oscilloscope screenshots is not audible from our experience. Research on that matter also shows that the phase shift cannot be heard [8]. We remain uncertain on the consequences of such phase shift for the software signal processing, so further research on that matter is necessary.

3.3 Headphone amplifier

The following screenshot (figure 10) shows the effect of the amplifier for a sine input signal. The amplification factor value is 100.

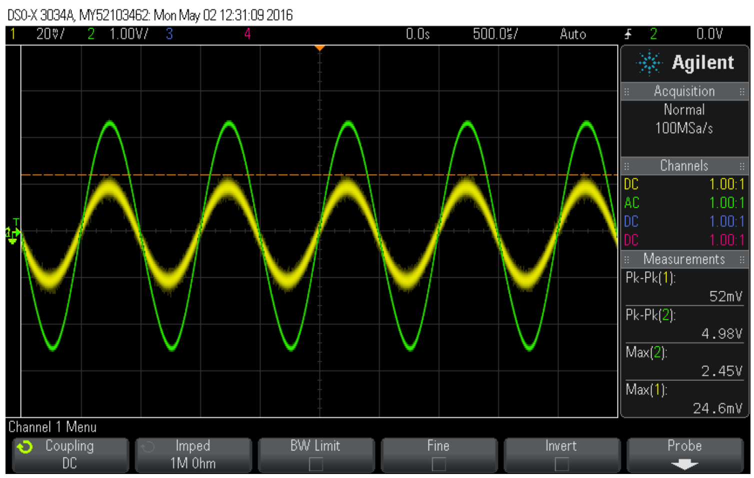

Figure 10 - Amplification factor

Figure 11 shows the output signal of the amplifier with the microphone signal as input. For this test, we fed the microphone with a sound with the same level as the loudest lung sound. In order for the filter to prove satisfactory, we needed the output to be close to the voltage value V_{min} found in Equation 2.

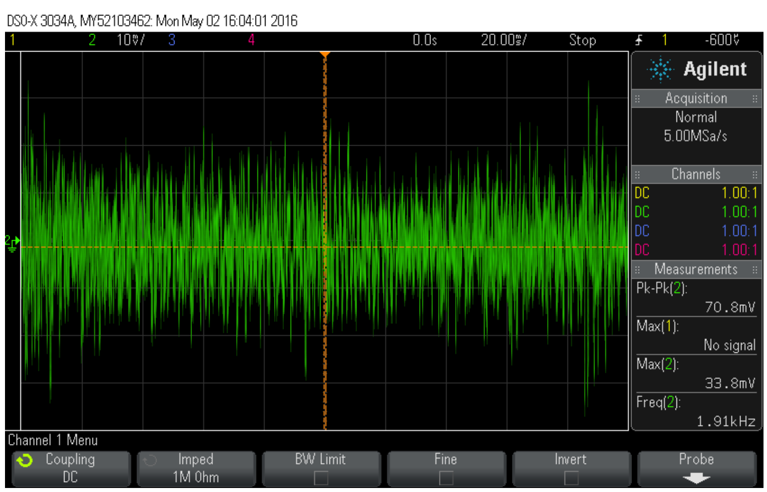

Figure 11 - Amplifier output for max level sound

With this output voltage, the doctor should tolerate this level of sound

3.4 Power unit

The main requirement for the battery is its lifetime.

To verify that the battery lifetime is at least 10 hours, we measured the current draw of each component, and then we deduced the battery lifetime knowing the power unit's capacity.

The current running through each operational amplifier is 2.5mA, and the one running through the Bluetooth module is 95mA. Equation (3) gives the expected alkaline battery lifetime with those measurements.

$$T = \frac{2*625\ mAh}{(95mA+3*2.5mA)} = 12h15min \qquad (3)$$

The microphone current draw being really low, the cell-coin will last longer than the 9V batteries.

The result found is adequate with our requirement.

3.5 Software

Since the hardware part couldn't be connected to the software, we performed it on lung sounds found in medical articles [9]. We had ten sounds; 5 of them were said to be sick people's lung sounds, and five were healthy people's sounds. Among sick people's sounds, we had two wheezes, two fine crackles and one coarse crackles. All the sounds were detected properly except for the coarse crackles file. So 1 out of the 10 sounds wasn't diagnosed properly, which gives 90% of success instead of the 95% desired.

However, the latency requirement was fulfilled.

Below an example of one of the two wheezes file that was properly detected.

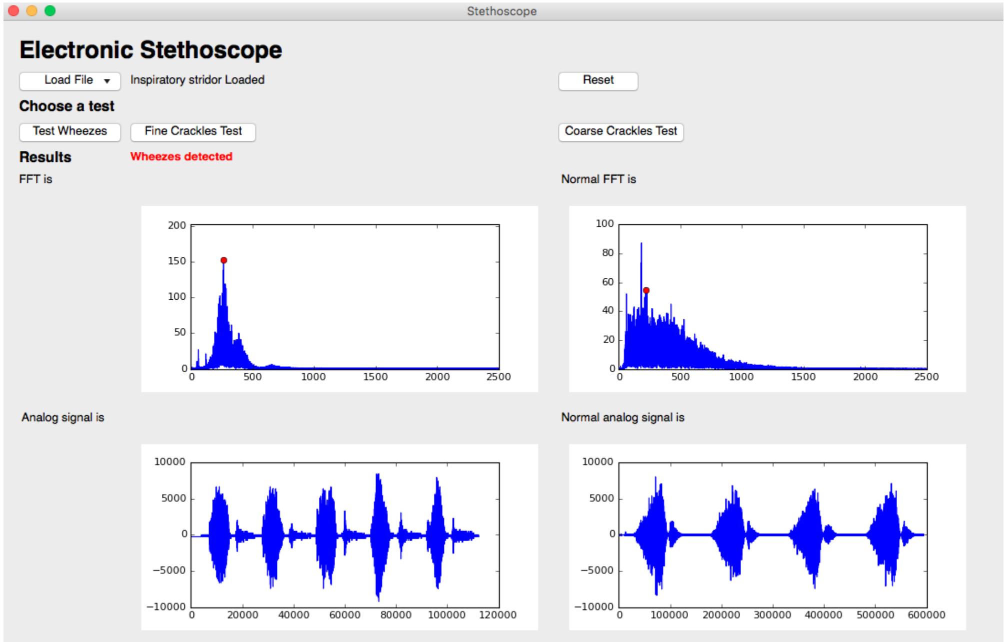

Figure 12 - Software's diagnosis on a wheezes sound file

5. Costs

5.1 Parts

Table 3 – Parts costs

Parts	Cost/unit	Number of units	Total
Electret condenser microphone	$1.42	1	$1.42
Numato's 8 Channel GPIO Bluetooth Module	$34.95	1	$34.95
9V Battery Energizer EN22	$1.75	2	$3.50
9V battery holders	$1.18	2	$2.36
Female jack	$0.15	1	$0.15
LT082 opamp	$0.25	3	$0.75
7805 voltage regulator	$0.90	1	$0.90
Resistors	$0.10 (average)	12	$1.20
Capacitors	$0.50 (average)	11	$5.50
10kΩ potentiometers	$1.00	2	$2.00
Red LED	$0.39	1	$0.39
Taxes	/	/	$5.31
Total shipping fees	/	/	$20.00
Grand Total			$78.43

We can state that those costs, even if the device is quite rudimentary, are way under the costs of existing electronic stethoscopes (average of about $350).

5.2 Labor

Name	Hourly rate	Total hours invested	Total=hourly rate*total hours invested*2.5
Robin	$28.00	230	$16,100.00
Fatima	$28.00	230	$16,100.00

6. Conclusion

6.1 Accomplishments & uncertainties

At the end of the semester, our device was able to record lung sounds, filter them and feed them to headphones. The software was able to provide and display a diagnosis to the user. We regret that we couldn't make the Bluetooth module work in time, to make sure the hardware and the software can work together properly. The use of another more documented Bluetooth module might be necessary.
Those two parts working together would allow us to have a bigger sample of lung recordings to ensure the success rate of the diagnosis is above 95% and is actually reliable for doctors.

6.2 Ethical considerations

We intend to follow the IEEE Code of Ethics during all the attainment of our project. Yet, we want to highlights some particular points.

Indeed, we want (5) to improve the understanding of technology ; its appropriate application, and potential consequences .

(6) to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations.

(7) to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others ;

Moreover, our device is a medical device. In that regard, every diagnosis made by our stethoscope has to be considered as a "preliminary diagnosis" that has no value without further tests and medical judgments. Our device's goal is only to guide the doctor towards a diagnosis, but does not in any case give a diagnosis that can be considered final.

6.3 Future work

As a future work, we would like to ensure the bluetooth transmission between the hardware and the software.

Furthermore, since we now know the microphone localization during the sound capture has an importance, we consider adding microphones and update the software to take their position into account.

The design can be improved in a lot of ways:

- The mechanical design of a stethoscope head would allow the recording of clearer sounds and prevent the proximity effect detected of electret microphones.

- Our filter is well-designed for our objectives but with more accurate medical data, the detection of other symptoms might require the use of FIR filters.

- As stated above, the power unit design can also be greatly improved.

References

[1] Jerad Lewis, “Understanding Microphone Sensitivity”, Analog Dialogue, web page, 2012. Available at:http://www.analog.com/library/analogdialogue/archives/46-05/understanding_microphone_sensitivity.html?doc=an-1328.pdf

[2]D. Garthe, “A fiber-optic microphone”, Institut für Übertragungstechnik und Elektroakustik, Technishe Hochschule Darmstadt, 1991.

[3] Andrès E, Reichert S, Gass R, Brandt C, Kehayoff Y. “La séméiologie pulmonaire à l'ère de la médecine factuelle”, *La Revue de Respir,* 2007.

[4]Sonia Charleston-Villalobos, Ramon Gonzales Camarena, « Crackle sounds Analysis by EprclMode Decomposition »,2007 [Online]

[5]Abraham Bohadana, Gabriel Izbicki, Steve S Kraman, « Fundamentals of Lung Auscultation », The new England Journal of Medicine,2014 [Online]

[6] Shure customer help, “Understanding Earphone/Headphone Specifications”, *http://shure.custhelp.com*, 2003. [Online]. Available: http://shure.custhelp.com/ app/answers/detail/a_id/2991/~/understanding-earphone-%2F-headphone-specifications. [Accessed 14-Apr2016]

[7] "How to Build the CMoy Pocket Amplifier", *Tangentsoft.net*, 2009. [Online]. Available:https://tangentsoft.net/audio/cmoy/. [Accessed: 12- Apr- 2016].

[8] Introduction to the Basic Six Audio Tests, *http://www.ap.com/solutions/introtoaudiotest/phase* webpage, [Accessed 3-May-2016]

[9] Easyausculation.org, « Basics of lung Sounds », 2015 [Online]

http://www.easyauscultation.com/cases-waveform?coursecaseorder=1&courseid=201

Appendix A Requirement and Verification Table

Component	Requirement	Verification	Verification status (Y/N)
Software	1. More than 90% success rate in adventitious sounds detection 2. 1min+/-30s latency	1. - Record 10 lung sounds (5 sick patient, and 5 healthy) - Open them in the software and run it - Make sure the diagnosis was correct for more than 9 people 2) - Run the software for different signals - Make sure the process remains between 30s and 1min30s	N Y
Filter	1. attenuation <6dB in the passband (50Hz;2500Hz) 2. attenuation>12db in the [0.;30Hz[U]6000Hz+ band	1. - Use a 5V sine signal as filter's input. - Change frequency between 50Hz and 2500Hz - Make sure the signal's amplitude is never under 2.5V 2) - Use a 5V sine signal as filter's input. -Change frequency between 0 and 30Hz and above 6000Hz - Make sure the amplitude is never	Y Y

		above 1.25V	
“Battery”	1. The device has to be able to last at least 10 hours without changing the batteries.	1. - Measure total current draw of the device (for the BT module use the maximum draw given in the datasheet 95mA) - Calculate : (Battery capacity)/(total current drawn) - Make sure the value obtained is over 10 hours.	Y
Headphone amplifier	The device has to provide 0.5mW to our earphones (imp=9 ohms, 96 dBSPL/mW)	-Plug the oscilloscope to measure the output voltage of the device. -Feed the mic with sound coming from a phone at the lowest volume (we assume this will be the max volume of a lung sound) -Make sure the output voltage is >0.067V	Y
Microphone	Capture frequency range : 50Hz – 2.5kHz	Feed known frequency signals to the microphone with speakers. Make sure the microphone is able to record all signals in the 50-2500Hz band.	N