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Using Low Cost Embedded Systems for Lung Sounds Auscultation and Analysis

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Abstract

This work explored a different way to measure lung sounds (i.e. cough and wheezes) by using embedded systems and an electronic microphone. This approach used low cost devices and the results were compared to a current state of the art device, Littmann 3200.

Several versions of prototypes were built because the sound provided by the circuit was full of noise. Wireless transmissions (Bluetooth and Wi-Fi) were intended to be used, but it was not possible to conciliate both real-time data and wireless transmission.

After tested the developed prototype, overall we obtained good results either on auscultating cough (sensitivity 76.97% $\pm$ 31.16% and specificity 99.83% $\pm$ 0.01% versus sensitivity 83.90% $\pm$ 31.97% and specificity 99.97% $\pm$ 0.00% of the Littmann), on comfort (average of 9 out of 10, same as the Littmann) and costs (41€ versus 350€ of the Littmann). On the other hand, it did not last a full day (neither the Littmann) and the sound quality was bad (the Littmann was good). Although one test contained wheezes, it was not possible to conclude anything related to this adventitious sound.

At the end, our prototype had good results, having failed in some aspects that did not make it completely successful.

Keywords: Wheezes, Cough, Embedded Systems, Real-time lung sounds acquisition

Resumo

Este trabalho pretende explorar diferentes formas de auscultar som pulmonar (por exemplo, tosse e pieiras) usando sistemas embutidos e um microfone eletrónico. Esta abordagem usa dispositivos de baixo custo e os resultados foram comparados com o estado da arte para este tipo de dispositivos, o Littmann 3200.

Várias versões do protótipo foram construídos devido ao ruído que estava presente no som. Foi tentado usar transmissões sem fios (Bluetooth e Wi-Fi), mas não foi possível conciliar a transmissão em tempo real com a transmissão sem fios.

Após testar o protótipo, obtivemos bom resultados tanto na auscultação da tosse (sensibilidade 76.97% ± 31.16% e especificidade 99.83% ± 0.01% contra sensibilidade 83.90% ± 31.97% e especificidade 99.97% ± 0.00% no Littmann), conforto (média de 9 em 10, o mesmo que no Littmann) e nos custos (41€ contra os 350€ do Littmann). Em contrapartida, o protótipo não durou um dia inteiro ligado (tal como o Littmann) e a qualidade do som foi má (ao passo que a do Littmann foi boa). Apesar de um dos testes conter pieiras, não foi possível concluir nada relativamente a este tipo de som.

No final, o nosso protótipo obteve bons resultados, tendo falhado nalguns aspectos que não o tornaram completamente bem-sucedido.

Palavras-chave: Pieiras, Tosse, Sistemas Embutidos, Aquisição de Sons Pulmonares em Tempo Real

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Acronyms

ADC	Analog-to-Digital Converter
AP	Access Point
BLE	Bluetooth Low Energy
BMI	Body Mass Index
COPD	Chronic Obstructive Pulmonary Disease
ECG	Electrocardiography
EIT	Electrical Impedance Tomography
FRX	Functional Requirement X
HUC	Hospitais da Universidade de Coimbra
IoT	Internet of Things
LCD	Liquid Crystal Display
LE	Low Energy
MCU	Micro-Controller Unit
NFRX	Non-Functional Requirement X
Op-Amp	Operational Amplifier
RTOS	Real-Time Operating System
TF-WD	Time-Frequency Wheeze Detector
WWS	Wearable Wellness System

Chapter 1

Introduction

The aim of this chapter is to introduce the theme of the thesis, the motivations and explain how we are going to obtain the results. At the end there is an overview of the entire document.

1.1 Motivation

Over time, the stethoscope suffered changes that improved the amplification of the sounds and, consequently, better diagnoses [1]. During the 20th century, some improvements were made in order to reduce the weight of the device so it could be easier to use, improving sound quality and adding filters, among others. In that epoch, the first electronic stethoscopes that allowed to deepen the amplification of lung/heart sounds started to came out. Since their existence, the devices are used to listen to lung and heart sounds. If a person has symptoms of some kind of respiratory disease (e.g., wheezes, crackles, cough, among others), the physicians will use the stethoscope and try to figure out what kind of problem the patient has. Today, Littmann is one of the biggest companies that manufactures medical devices (stethoscopes are included) and their Littmann 3200 electronic stethoscope is one of the best devices for auscultation that exists because of all of the features that it has. But there are some problems with this equipment: it is very expensive and it is not wearable.

Human's anatomy is fairly complex, with different levels (organs, tissues, complex systems - respiratory, digestive, urinary, nervous, etc). Having the same equipment analyzing and collecting data from them can save time, but there are organs that are very important standalone. One of them is the lungs. They are primary organs for the respiration, helping extracting the oxygen from the air and transfer it into the blood, releasing, after that, carbon dioxide [2]. Having this importance, it is crucial to have a system that can auscultate them, even if it is the only function that it does (it does not add extra complexity to the system and it is focused only on the lungs).

Recent technological advances brought to us tiny devices that are called embedded systems [3], and they are in a new technological era that allow to connect everything to the internet, the so-called Internet of Things (IoT) [4]. Some companies started to show up with new technology and equipment that could improve life quality in many ways: education, science, health, environment, among others. They are known not only for being tiny, powerful, different, but also for being cheap. Nowadays, Arduino and Raspberry are the main manufacturers of the devices and both have extra components (microphones, temperature sensors, humidity sensors, among others) to which we can connect and expand the system to serve multiple purposes.

Knowing that the electronic stethoscopes are expensive and not wearable, and also knowing that embedded systems opened a new era by introducing devices that have the same capabilities of a computer, but are smaller, why not use them to create a cheaper, smaller and efficient electronic stethoscope?

1.2 Goals and Approaches

The main goal is to create a prototype that allows the acquisition, processing and detection of adventitious sounds, focused on cough. The prototype will be comprised by:

- Microphone - it will be embedded in a stethoscope to increase mechanically the gain of the sound;
- Board - to allow the communication between the microphone and a third party component that will run algorithms to detect cough and wheezes.
- Electronic Components - used to stabilize the noise, remove extra current from the circuit, amplify the sound, among others.

The components will be connected together and we aim that the final result can translate into a low cost and reliable system that can detect both cough and wheezes. With the microphone connected to the board, using the electronic components needed (capacitors, resistors, amplifiers, among others), we can gather the data inside the board and apply pre-processing methods to send, using wireless communications, to a third party component (phone/computer) and, there, use the algorithms to process the sound to obtain the results. Our research group has experience and algorithms for both types of sounds which is helpful to developing and testing the prototype correctly.

This will work as a **proof of concept** for the use of low cost solutions, with embedded systems. If this solution is successful, the work can be continued with the improvement of the prototype, either adding new types of sensors (e.g., respiratory/heart rate, etc.) or using different algorithms to process other types of adventitious sounds, to increase the robustness of the solution.

1.3 Main Contributions

During the development of the project, we made studies and researches about several important characteristics for the project (components, systems, algorithms, among others), but sometimes we faced some limitations that we needed to overcome. Starting with the contributions:

- We reviewed the current state of the art for monitoring systems, embedded systems, algorithms and traditions stethoscopes.
- We developed a functional low cost prototype that has an acceptable performance acquiring sounds.
- We studied the quality of the sounds provided by our prototype and the Littmann 3200 and did not have good results.
- We compared both cough and wheezes sounds from our prototype and the Littmann 3200 (despite only one case had wheezes) and obtained similar results.
- We also compared the comfort between using our prototype and the Littmann 3200 and obtained almost the same level of comfort.

Regarding the limitations:

- During the year we tried to contact several specialists (via several ways) but we did not succeed. Only during appointments we could clarify some doubts.

- During the study of the state of the art, we discovered that almost every project is no longer being developed or does not have any news, which did increased the difficulty to reviewed them.
- The embedded systems are recent and the technology is evolving during the years. During the year we faced very new products (i.e. Genuino 101 came output during 2016, the second version of the Raspberry Pi Zero - Raspberry Pi Zero W - was launched in March, 2017) that we could not test/use in our project. The advances in technology can increase the reliability of the prototype and, consequently, improve the sound quality.

1.4 Structure

The document has the following structure.

- **Chapter 2, State of the Art** - this chapter is divided into four main sections being (1) systems, where we study the different vests and projects that exist regarding the monitorization of adventitious sounds, COPD, among others, (2) algorithms for detection of wheezes and cough, a brief explanation of several algorithms that can detect wheezes and cough, (3) embedded systems, study the difference between some of the current boards that exist nowadays and (4) traditional stethoscopes, explaining the main differences between some models.
- **Chapter 3, Requirements** - this chapter describes the several non-functional requirements and their respective importance to the project. They were selected based on the products that exist nowadays and on the needs of the project.
- **Chapter 4, Materials and Methods** - the aim of this chapter is to describe, in detail, the materials and methods used on the project, such as: the positions where the measurement are going to be made, the algorithms used, wireless protocols for data transfer, electronic components used for the project and the architecture (for the system and for the prototype).
- **Chapter 5, Experiments** - this chapter aims to describe how we made the tests and how we solved the problems that we discovered. We also discuss some aspects regarding sound quality and present the results of the tests, including the comfort and power consumption.
- **Chapter 6, Conclusions and Future Work** - this chapter concludes all the work done during both semesters, discussing about the results obtained and what can be done in the future.
- **Chapter 7, Planning** - this chapter describes how the project was developed during both semesters, using *Gantt* charts. Regarding the first semester, the chart translates the real situation; for the second semester, two charts are presented, being the first one the plan made in the first semester and the second one the real work done; the difference between both charts is also explained in the chapter.

Chapter 2

State of the Art

Nowadays, there are several devices that can help collecting and processing data (sounds), but they are not perfect. Some of them lack on the build itself, others on the documentation (and, consequently, there is no way to describe or explore them further). Along with systems, there are always algorithms that will process the data and return the results.

With the objective of building a prototype to auscultate lungs sound and get similar results to the state-of-the-art electronic equipments, the recent technology (embedded systems) and the traditional stethoscopes will be studied and described, according to specific points (described in each section).

The aim of this chapter is to expose and describe systems, algorithms and embedded systems that exist, by showing their advantages and disadvantages and how they process sound to detect cough and wheezes (applied to the algorithms).

2.1 Systems

Currently, there are several systems that allows to auscultate lung sounds. Depending on the use, some are more expensive than others but, generally, the more expensive it is, the more features it brings to the user.

In this chapter, we are going to compare the technology that exists and show the advantages and disadvantages of each one.

2.1.1 Littmann 3200

The **Littmann 3200** is an electronic stethoscope that has a lot of features embedded in it [5]. This Littman is the second tier of the electronic stethoscopes from the brand, having extra features allowing a better auscultation. Some of the features are listed bellow:

- It has an **LCD interface** for better use of the device;
- It has a simple **control panel** where the user can interact with it and change some parameters (volume, the head - it will adjust digitally the way that the device records sounds [Bell or Diaphragm mode]);
- It can record **30-second sounds** and store them in the memory of the device.
- In this version, it adds **Bluetooth**, allowing to transfer the data from the stethoscope to a computer;
- It can cancel **85%** of ambient sounds that interfere with the measurements, ensuring that records only have body sounds;

- The chestpiece of the stethoscope has a technology to **reduce the frictional noise** that is generated;
- It can amplify the sounds up to **24x** the original, for cases where the sound is faint (i.e. the patient is obese or the clothes are a restriction to the measurement);
- It only uses one sound sensor, but the quality of it is very good, providing a *"sound experience similar to a high-end cardiology stethoscope*" [6].

The stethoscope is very good and the features that it brings makes it an interesting device for lung auscultation. But, there are some aspects that have to be considered when talking about the Littmann 3200, as it is possible to see in the list bellow:

- In the stethoscope documentation it is only mentioned that the device operates with a single AA battery, although they do not state how long does it take to the battery to run out of energy [6]. Having Bluetooth, Frictional Noise Removal and Noise Cancellation means that there are advanced algorithms that consume a lot of power to perform such processing;
- The stethoscope **is not wearable**, which means a patient cannot use it for a long period of time;
- It is an **expensive** device. Having plenty of good features raises the price, reducing the market around it (only hospitals and research centers are able to spend more money on an state of the art stethoscope).

After analyzing the advantages and disadvantages of this device, it is possible to conclude that it is an excellent stethoscope. Despite the price and the lack of portability, it does a great job recording, saving and sending sounds to a computer. Although it is good, the market is very small, being more accessible to health care professionals (cardiologists, critical care nurses, physicians, pediatric specialists, among others) and/or researchers.

2.1.2 VitalJacket

The **VitalJacket Project** is a comfortable shirt that allows 72 hours of continuous registry of the patient health [7]. The features are listed bellow:

- **Comfortable** and **easy** to wear;
- **72 hours** of **continuous registry** to increase the efficiency on a medical diagnosis;
- The device that registers the data is **small** and **light**; having those characteristics makes it possible to put it inside a pocket, in the shirt;
- The register device has a **color code** that allows the patient/medical professionals to be aware of the **state of the device**;
- It incorporates a **Bluetooth sensor**:
  - Making it easy for the patient to visualize the data that is being collected in real time;
  - To connect to a nearby device, that has an internet connection, used to send the data elsewhere (hospital, server, etc);
- It has an **accelerometer** and the collected data is processed and scaled, for an easier interpretation of medics (to check if the patient was walking, has cardiac problems, among others).

Although the vest has a lot of features embedded, there are some constraints that need to be taken care of. From the documentation of the vest [7], we can see that some points are missing or uncompleted.

- Concerning power consumption, they do **not mention it directly**. The only mention is when they specify that it can record 72 hours of data. Regarding the device that registers the data, because of its dimensions, it is not possible to know if it has a battery included or if it needs an extra component (i.e. AA battery) to power it up;
- The real-time visualization (that is possible to do, according to the documentation [7]) is only available **while not recording**, so, during a recording session, the patient cannot monitor what is being registered;
- In the website [8], there is a page that redirects to the distributors of the product. By consulting all of them (Sanro [9], Hogimed [10], Optima-Life [11] and TKL [12]), we can check than on December 15th, 2016, **none of them sells** the equipment. Having this constraint, it is not possible to check its price.

The vest has a lot of features but there are several problems that needed to be solved. The last update of the website was performed in October 2014, where they show some statistics about the the project[1].

2.1.3 NyxDevice Somnus Sleep Shirt

The **NyxDevice Shirt** has a lot in common with the VitalJacket. Despite one is for measuring hearth beats (VitalJacket) and the other for measuring sleep (NyxDevice Shirt) [13], both devices are wearable and have their own advantages and disadvantages. In the case of the NyxDevice Shirt, they are listed below:

- The vest is made with a **light** and **breathable material**, allowing for a comfortable sleep and for the patient to move freely;
- The sensors applied to the shirt are **very thin** so it can be applied to a shirt without forming a goiter;
- Like VitalJacket, the device that registers data is small and can **record data up to 5 days**. It will automatically start recording data when it connects to the shirt;
- The data collected during the night is transferred to their website while charging (during the day).

The team behind the project thought very well about the constraints and they use technology to overpass them. But it misses a lot of information regarding important aspects. Despite the last update was on 2011, the project was in a later stage of development. Some disadvantages about this project are listed bellow:

- There are **no news since 2011**. After some researches, we found that it was predicted to be launched in 2012 and the cost was around 100$ [14], but nothing was found (the website is very vague [13] and only by searching in other websites - that reference the product - we could find more information);
- Regarding **power consumption**, they only explain that the device can record up to 5 days, but they do not explain if it needs constant charging in the morning or if the device can record data during full 5 days or only nights.

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[1] http://www.vitaljacket.com/?p=1321 - last access: 26/June/2017

The project was in a very advanced stage, but suddenly **it stopped** and there is not any information about whether it reached the stores. According to the website, it would be a very good product for sleep monitoring (comparing to others[2]), but it never went further than the prototype.

2.1.4 Smartex Wearable Wellness System (WWS)

This is another kind of **wearable shirt** that can acquire various signals such as electrocardiograms, respiratory signal and body movements [15]. The respiratory signal is measured in the thorax and all the data is stored in an electronic device that, besides storing, will process that data. To complete the circuit, there is a software that will show the data and allows the user to manage it the way he wants.

Having the shirt those three sensors, the device is able to calculate and extract more values that are helpful for the patient to be aware of, as it is possible to see in the list bellow:

- **Hearth** and **respiration rate**;
- **Respiration signals**;
- **Posture** (lying, standing, etc);
- **Steps** by minute.

Summing up, the vest has plenty of functionalities, but when focusing on the respiration and the characteristics (price and power) of the vest, there are a lot of disadvantages.

- Unlike the previous models, there **is not any indication of the power usage**, neither indirectly (by number of days that it can, continually, collect and process data) or directly (by presenting the values on the website);
- The respiration module of the shirt is **very vague** (the documentation is very short and does not explain everything [15]), but it is said that the position of the respiration sensor is on the thorax (it does not specify where exactly) and it will extract the respiration rate. This does **not permit the detection** of adventitious sounds; they only process the signals to extract the rates. It is not possible to know if the rates can show any kind of problem, but if they actually show, the documentation **doesn't say anything** about that and **which values do they get**;
- With a lot of detail in the production and elaboration of the vest makes it very expensive. According to the site, the WWS costs **398€**[3].

The lack of information about some aspects on the website [15] was the main issue about the vest. They described all the sensors they have added and also explained the extra parameters that those sensors can help extract, but it **was not possible to find any technical details** regarding to power consumption, how is the shirt organized (where is the device that stores and processes the data, its size) and how can the shirt (the device) communicate with the software (that allows visualization of data).

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[2] In this case, it is possible to compare with the **ResMed ApneaLink Air Home Sleep** - http://somnussleepcenter.com/service/home-sleep-testing/ - even though the purpose of the ResMed is for detecting apnea and the NyxDevice is for monitoring the sleep (not specifying any kind of disease).

[3] Last consulted on 17/December/2016

2.1.5 Welcome Project

Unlike the other projects, the Welcome Project is still under development and it aims to build a vest that can integrate a high number of sensors to monitor sounds, ECG, EIT, 3G acceleration, among others[16]. The documentation provides plenty of information about technical details and others. Some of the features are listed below.

- The vest will be **easy to wear**;
- The way that the vest will be made, it is **easy to maintain** and it can be washed normally;
- It will provide sounds with **high-quality**, using two sound sensors in the thorax;
- The way that the vest will be made is by using a different kind of cables (dry electrodes), making it comfortable for every day use. This feature will not affect the signal quality;
- It will incorporate sensors for detecting various **COPD** (Chronic Obstructive Pulmonary Disease) symptoms:
  - **Estimated amount of oxygen in the blood (SpO2)**;
  - **Electrical Impedance Tomograph (EIT)**;
  - **Chest Sounds** (crackles and wheezing);
  - **High Spatial Resolution ECG**;
- Besides detecting the symptoms, it will have an **accelerometer** (just like the VitalJacket) that will allow to detect patient position (lying, standing, moving, etc; this information is useful for the medic).

The vest aims to be very different from the technology that exists (it compares to DeepBreeze, but this project does not have any new information since 2014 and the website is no longer available), not just by being wearable, but also because it will enable ambulatory monitoring. The patients will not need to be seated or lying down, they can be walking in the comfort of their home.

One of the main issues of this project is that clinical trials were not yet performed to assess the outcomes of the project. They had to change some of the initial goals (e.g., the number of sound sensors was drastically reduced from 10 to 2, as usual in a research project - it is not possible to predict all the risks at the beginning) to adapt the vest to the new conditions. Because of that reason too, there is no information about the price that it would be sold, but by consulting the available documentation (on the website [16]), it is possible to see that, with a huge number of features and state of the art sensors, the **price will be high**.

With all of these characteristics, the main purpose of the vest is to be used by people that need to be **monitored regarding their COPD** condition. It will be available in hospitals, for physicians to give to a patient to, then, use it for a couple of days and collect all the information that they need and, finally, process it and return the results.

2.1.5.1 Comparison

All the systems are different, but the aim is the same: provide better systems to measure pulmonary and cardiac sounds. For that, they try to reach a balance between comfort, power consumption and price.

One of the main problem is that some of the projects do not have any updates for a long time, which is bad for comparison purposes. Although the Welcome project is still a work in progress, there are not any actual results (either a vest or tests) that can allow for any kind of comparisons.

With that, the only solution available for testing is the Littmann 3200. It is very expensive and not wearable, but it contains impressive features that can improve the results (and possibly mark the differences for the prototype).

2.2 Algorithms for the Detection of Wheezes and Cough

Nowadays, the evolution of science brought advances in health care treatments, new ways to discover diseases, sophisticated algorithms to detect problems, among others. Every vest that has integrated sensors that can detect if a person is coughing, speaking, sneezing or with any respiratory problems (crackles, wheezes, and so on) needs to have an algorithm that can recognize those sounds and return a result with the highest possible reliability. Regarding our project, we are going to focus on cough and wheezes. Since they have completely different sounds spectrogram, we cannot use the same algorithm to detect both problems.

With that said, we are going to see different methods to detect both wheezes and cough.

2.2.1 Wheezes

Every algorithm has different methods to achieve the result, having different feature extraction, feature selection, preprocessing, datasets, etc. To detect wheezes, we are going to check some processes that exist and how they are used to achieve those results.

- Using the spectrogram and musical features - this method makes use of image that wheezes cause in the spectrogram, in higher frequencies, and the musical nature of the adventitious sound[17]. The best result was 90.9% (sensibility) and 99.4% (sensitivity).
- Using a time-frequency analysis - wheezes are characterized by higher frequency peaks (between 100Hz and 1500Hz[18]) and longer duration time (150ms), being very different from the other adventitious sounds (less that 300Hz and 100ms), being possible to study the wheezes in both time and frequency domains, searching for peaks in the resultant spectra. [19][20]. The best result was 95.5% (sensibility) and 93.7% (sensitivity).
- Using pattern recognition - using various methods for feature extraction (Fourier Transform, Linear Predictive Coding, etc) and classification (Vector Quantization, Gaussian Mixture Models or Neural Networks), with a dataset, it is possible to study different combinations and reach to good results[21]. The best combination result in a sensibility of 94.6% and sensitivity of 91.9%.
- Using auditory modeling - it is a combination of time-frequency and spectrogram. The idea is to use the time-frequency matrix to detect peaks and, at the end, produce the spectrogram with the wheezes marked[22]. The results are not known.
- Using histograms of sample entropy - by getting the time-frequency divided in the two respiratory phases (inspiration and expiration), the sample entropy is applied and the histograms are build, with the mean distortion being used as discriminative feature to detect wheezes[23]. The best results were sensitivity of 80.4% (inspiration) and 95.7% (expiration) and sensibility 90.2% (inspiration) and 100.0% (expiration).

From the five different algorithms studied, four used the same base method: time-frequency analysis. Although all the results are above 90%, with the exception of the sample entropy algorithm (they divided the inspiration and the expiration), it is not possible to compare them because of the differences on the datasets.

2.2.2 Cough

Cough has a different behavior when compared with another adventitious sound. The frequencies are normally between 300Hz and 500Hz, in a healthy subject, and 500Hz to 1200Hz, in a subject with respiratory diseases[24], and it can contain wheezes (this case is typical in asthma).

- Using neural networks - starting by preprocessing the data, by segmenting into 4ms frames and removed irrelevant sound (noise and silence), and then, using a network consisted by 2 convolutional layers, 2 fully connected layers and a classification layer, and having 30% of the input data for training, they evaluate the remaining data[25]. The best result was 94.0% (sensitivity) and 91.7% (specificity).
- Using spectral content descriptors and pitch-related features - first apply preprocessing methods (using a band-pass filter and remove near-silent segments), then extract features (pitch and spectral) and classify (using the Logistic Regression algorithm)[26]. The best result was 93.4% (sensitivity) and 83.4% (specificity).

Both algorithms used the same method: pre-processed the data, divided for training and testing and make a dataset resultant of training to be used in the classification. One main different between the results is that the second algorithm is also getting the speech results aggregated with the cough; even with that, the results are not very different and the methods applied by both are practically the same.

2.2.3 Remarks

In both sections we reviewed, briefly, some algorithms that were identical between them. In both sections there are algorithms made by our research group ([17] and [26]) that we are going to use for the project. They are recent and because the results obtained when compared with the other algorithms are similar, we decided that they fit in the project.

2.3 Embedded Systems

This section refers to the systems that are going to be tested and to explain (in detail) each one of them. They were chosen according to some constraints, as follows:

- **Wearability** - they are small and can fit on a simple t-shirt/pocket.
- **Cost** - the devices are cheap[4].
- **Low Battery Consumption** - although nowadays there are power banks with a considerable amount of energy storage, this is a critical point and, hence, all the analyzed devices have low consumption.

2.3.1 Arduino Lilypad USB

The Arduino Lilypad USB has 5cm diameter which is very small and with this size, it fits very well in a t-shirt. The Arduino was built thinking on running code directly, with **no latency** between measurements, which means that each routines takes the exact same time[5]. The Arduino is equipped with a micro-controller ATmega32u4 and it operates with a voltage of 3.3V. This is a very low voltage for a device that can have connected hardware and collect the data in real-time.

Unfortunately, the Arduino is not a powerful device because:

- It is equipped with a **low-power MCU** (micro-controller unit) clocked at 8MHz, but there is not a way to process a lot of information in the system. It runs code in an almost deterministic fashion (because of the MCU).
- Because of its simplicity, the board does not count with much RAM (2.5KB) or Flash (32KB). These low values can compromise storage if, for example, we have a Bluetooth or Wi-Fi adapter connected to send data to a server and we can't send the data quickly enough.
- It does not have any Bluetooth/Wi-Fi connection so it needs an external piece of hardware to make it possible to send data to a phone/server.

2.3.2 Raspberry (Pi Zero)

The Raspberry (Pi Zero) is a small single-board computer that differs from the construction which follows a different philosophy from the Arduino. It has a single-core 1GHz CPU, which means that it is possible to acquire data in near real-time and processing it in the board, eventually using a Real-Time OS or RT middleware stack. Besides that, it has 512MB of RAM and a Micro SD card slot for a card with an operating system[6].

Despite the positive aspects mentioned, there are some problems related to the way that the system is built and about the functionalities:

- There are 40 digital ports, with **no analog acquisition capabilities** - an extra component (MCP3008 - **section 4.4.1**) is need to simulate this kind of ports.
- Preemption - being a small computer means that the processor executes tasks in concurrent mode, under control of a conventional operating system[7]. In this kind of environments, the **determinism is not a priority** so the same task can have fluctuations on the execution time.
- Like Arduino Lilypad, it does not have a Bluetooth/Wi-Fi hardware pre-built.

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[4] See **table 2.1** for a more detailed information.

[5] This is important in the Health Area because we want to ensure that we are collecting the same number of measurements in a certain time window.

[6] NOOBS or Raspbian. **It is possible to run Python3 in the Raspbian.**

[7] The OS - **Linux distribution** - was not designed to be deterministic.

2.3.3 Genuino 101

The Genuino 101 is the biggest board of the three that we are considering. Despite being very similar to the Arduino Lilypad, it has changes that can help improving the project. It starts with a 32MHz Intel Curie module (a x86 core and a DSP, Digital Signal Processor) - this means that it can be used to make some pre-processing before sending the data to other device/server, with the help of the **Bluetooth Low Energy** module that is integrated within the board. Also in the board, there is a **accelerometer**.

Although having an Arduino with CPU is good to have a mix of hardware and software for the project, some aspects have to be taken into count:

- Like the Arduino Lilypad, this board has a very small RAM (24KB) and storage (196KB). Increasing the storage is possible, but it will increase the board height.
- This board costs more than the other two, but this is understandable because of the extras - it has Bluetooth integrated;

2.3.4 Comparison

	Arduino LilyPad	**Raspberry Zero**	**Genuino 101**
CPU	-	**1GHz single-core**	32MHz dual-core (x86)
RAM	2,5KB	**512MB**	24KB
Storage	32KB	**Variable**	196KB
Analog Ports	4	-	**6**
Operating Voltage	3.3V	**3.3V / 5V**	**3.3V (5V tolerant)**
Preemption	**No**	Yes	**No**
Size	5x5cm	**6.5x3cm**	6.9x5.3cm
Price	22.19€	**4.61€**	28.4€
Extras	Micro USB	Mini-HDMI Micro USB (Power & Peripherals)	**RTOS*** **Bluetooth LE*** **Accelerometer**

TABLE 2.1: Comparison between the **Arduino Lilypad USB**, **Raspberry (Pi Zero)** and **Genuino 101** according to important characteristics for the project. **RTOS*** means Real-Time Operating System and **Bluetooth LE*** means Bluetooth Low Energy.

By viewing **table 2.1**, it is possible to notice that there is not a single device that can do everything without adding/modifying extra components. We have to take into account factors such as:

- **Analog Ports and Operating Voltage** - having an extra device to simulate analog ports will increase power consumption and, consequently, it can last less than the Arduino. Also, having more Analog Ports means that more devices can be connected to the board (increasing the power consumption).
- **Preemption** - when a patient needs to check, regularly, information regarding his health, we assume that the data are collected exactly at the same time, with no variance between

the times of two measures. Raspberry has this problem and it can be solved if we use **PREEMPT_RT** Linux Kernel Patch [27] (see **section 2.3.2** where the preemption on the Raspberry is discussed). This will boot Linux, with improved interrupt handling and functional call determinism, in the Raspberry [28].

- **Communications** - the data are not going to be stored in the devices. For that, a communication with a phone/server is needed and, consequently, a Bluetooth/Wi-Fi module needs to be present. Only the Genuino 101 has a Bluetooth module embedded and it *"is optimized for low power use at low data rates, and was designed to operate from simple lithium coin cell batteries"*[29].

The prototype was tested on the three systems but, at the end, the characteristics that matter the most (costs, size, wearability, complexity of the build) was important to decide which one could be used for a final product.

2.4 Traditional Stethoscopes

In this section we detail two different stethoscopes. Some specifications and a critical point-of-view are given so it is possible to compare solutions (in terms of specifications). Both models were chosen according to the characteristics of the project.

- **Littmann 3200** - Electronic stethoscope that can handle and analyze signals in real-time, applying filters to reduce noise and record sounds [5];
- **Logiko Echo** - Traditional stethoscopes that are used for cardiology and pneumology [30] [31].

2.4.1 Littmann 3200

As mentioned in section **2.1.1**, this is an electronic stethoscope produced by Littmann [5]. It is an **expensive** product (but its features justify the price) that can analyze sounds with high performance. **For a detailed description, consult 2.1.1.**

2.4.2 Logiko Echo Stethoscopes

Logiko Echo Stethoscopes are very **cheap** and are built by an Italian company, Moretti. Depending on the use, there are a lot of different types and there are three different stethoscopes that were studied for the purpose of this thesis:

- **DM130** - the smallest stethoscope from the brand and its head makes it possible to put a small microphone inside it (the head has 45mm diameter and 10mm height). Although it is suitable for pressure measurement, the sounds coming from the lungs were perfectly audible when testing the device. It is made with anodized aluminum [31].
- **DM500** - With the same dimensions of the DM130 (despite a larger height), this stethoscope is suitable for high and low frequencies. Having this interval, means that heart sounds can be heard clearly, so we discard this one. It is made with anodized aluminum [31].
- **DM530** - it is very similar to the DM500 but it is made with stainless steel instead of anodized aluminum. It is bigger than the previous two stethoscopes [31].

Table 2.2 shows a brief compilation of the three stethoscopes.

	DM130	**DM500**	**DM530**
Material	anodized aluminum	anodized aluminum	**stainless steel**
Diameter (head)	45mm	45mm	46mm
Height (head)	**10mm**	20mm	20mm
Suitable Use	pressure measurement	high/low frequency sounds	high/low frequency sounds
Lung Sound	**well, with low noise**	well, but with some noise from the heart	well, but with some noise from the heart
Price	**4.99€**	7.80€	32.20€

TABLE 2.2: Comparison between three models of Logiko Echo Stethoscopes.

From the table 2.2, there is one model that can satisfy the needs for this project: the DM130. Although the material is not the best, the height of the head and the preliminary tests results were good, in comparison with the other models. The suitable use for the three models might not be the indicated for the project, but tests were made, by having the stethoscope **in three different positions**, has shown in **section 4.1**, resulting in a clear sound[8], which indicates that this is the best model to use and compare. About the price, DM130 costs less, among the three models.

2.4.3 Comparison

Comparing an electronic stethoscope with a traditional one is not fair because they are totally different and it is not possible to even find a similarity between both of them (despite they are used for the same function, but one has extra functions that makes it significantly better). On the other hand, the comparison will be made at the end of the project (with the results available) by comparing the obtained sounds from the electronic stethoscope (Littmann 3200 - **section 2.4.1**) with the prototype built.

Regarding the traditional stethoscopes (**section 2.4.2**), a small comparison has been made (at the end of the section). With a preliminary work made, we contacted a pneumologist that helped us choosing and explaining why one stethoscope is better than others (for specific measurements). According to a worker[9] of the Pneumology Department of Hospitais da Universidade de Coimbra (HUC), *"there are not specific stethoscopes for pneumology"*.

2.5 Remarks

In this chapter we reviewed different methods for the acquisition of cardiac and pulmonary sounds, describing the different advantages and disadvantages regarding their features, different algorithms to detect wheezes and cough regarding their different methods to detect them, and also the three different embedded systems (with their advantages and disadvantages) and traditional stethoscopes (that are going to be used as the head of the prototype).

Starting with the systems, only the Littmann 3200 fulfilled the requirements and the documentation was clear; the others were not found on sale or are not made yet. In the algorithm's section, we analyzed five algorithms for wheezes and two algorithms for cough; algorithm [17], for wheezes, and algorithm [26], for cough, are going to be used for the purpose of the project. Regarding the embedded systems, they are very different from each other and have different characteristics; despite the huge difference between the higher and lower price of the boards, the next chapters will help to decide which board better fits in the project. Finally, regarding the traditional stethoscopes, and having the opinion of a person that works in the area, the chosen stethoscope will be the DM130.

With the different materials and methods analyzed, we now have all the components to detail the requirements and focus on having a prototype than can fulfill them and achieve good results.

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[8] In this case, clear does not mean that it is 100% noise free; it means that the lung sounds are audible with low noise. In the surroundings there was no noise detected during the tests.

[9] For professional reasons, the name cannot be disclosed.

Chapter 3

Requirements

Some characteristics of the project are related to **the costs**, **the efficiency of the data collection** and **wearability**. In **chapter 2**, **State of the Art**, there were some examples of works that were/are being conducted and, based on them, it is possible to understand what are the needs for a similar project.

With that, this chapter shows the function and non-functional requirements for a device that can record and process sounds, and showing the processed data to the user. There are three different requirements that will be fundamental to the project:

- **Wearability** - achieve a non-invasive method that can allow collecting data from the patient (in a certain part of the its body).
- **Performance** - having low power consumption device, the results cannot deviate by 5% from those that already exist and are documented.
- **Costs** - the costs of construction a device that can allow auscultating lungs cannot be high.

Each table will have an identifier (to allow the usage of the requirements further on), the correspondent category, the creation and the last modification dates and a prioritization category according the **MoSCoW** method:

- *Must have* - **critical** requirements.
- *Should have* - requirements are **important but not critical**.
- *Could have* - requirements are **desirable but not critical**.
- *Won't have but would like* - **non-critical requirements** and planned for further versions;

.

The **Identifier** field represents the type of the requirement (functional or non-functional), being:

- **FRX** - **functional requirement** number **X**.
- **NFRX** - **non-functional requirement** number **X**.

Table 3.1 shows a brief summary of all the requirements. Appendix A contains the detailed tables where each requirement is described and explained.

ID	Name	Category	Prioritization
NFR01	Easy to manage/use	Wearability	*Must have*
NFR02	Comfortable build to be used by patients	Wearability	*Must have*
NFR03	Non-invasive medical build for recording the sounds	Wearability	*Must have*
NFR04	Lightweight medical build for recording the sounds	Wearability	*Should have*
NFR05	Wireless communications	Performance	*Must have*
NFR06	Having a build that has low power consumption	Performance	*Must have*
NFR07	Classification results comparable to state of the art systems	Performance	*Must have*
NFR08	Sufficient sampling rate for an ADC	Performance	*Must have*
NFR09	Sound quality	Performance	*Must have*
NFR10	Sound amplification using an op-amp	Performance	*Should have*
NFR11	Pre-processing data in the embedded system	Performance	*Should have*
NFR12	Processing data in the embedded system	Performance	*Could have*
NFR13	The build cannot be expensive	Costs	*Must have*

TABLE 3.1: Summary of the requirements, represented by the identification (ID), name, category and prioritization.

Having made the requirements will help to focus on the build and testing the prototype. They were made based on the state of the art of the systems and their best features, so fulfill the requirements will be very good, but challenging.

Chapter 4

Materials And Methods

Nowadays there are different methods to auscultate lungs (as shown in chapter 2) that help record and process the sounds to, then, help detecting if there is any pathological condition. For this project, the methods are focused on detecting cough and wheezes and, for that, a detailed description is provided to understand how that is going to be made.

The aim of the chapter is to describe, in detail, the methods and materials of the project. Starting with the measurement protocol, where the places for the measurements will be defined based on pre-tests made after the built of the prototype and on current state of the art papers. After that, the chosen algorithms are going to be detailed to better understand how they work. With the objective of having wireless communication, we are going to discuss between Bluetooth and Wi-Fi which one fits better in the project, taking into account different constraints (battery consumption, range and data transferring rate). To build a prototype we need to study different electronic components that can be used to improve sound's quality and output (i.e. operational amplifiers, analog to digital converters, etc). With all these components studied, we finalize by defining the architecture for both the system itself and the prototype, in the last section.

4.1 Measurement Protocol

To detect wheezes and cough, the stethoscope should be positioned in one of the places illustrated in **figure 4.1**. [17]

(A) Front.

(B) Back.

FIGURE 4.1: Positions to acquire lung sounds (specially to detect **wheezes**). Both images were taken from [17].

In [17], they acquire data from **2 positions** depending where the sound was better heard. In this project, it will collect from **2 positions** also. One issue about hearing lung sounds is the heart beats and that is not possible to overpass because when we use a stethoscope the head of the device is going to, mechanically, amplify the sound, making the heart beats audible (even if it is not very high), as it can be seen in figure 4.2. This happens because the **heart** is situated mostly behind the left lung (figure 4.3[1]) and so, to slightly overcome the problem, one solution is to listen to the sounds in the right side of the body. Because some of the positions mentioned in [17] suffer from this problem (**2**, **4** and **6**), we will only test on the other three positions (**1**, **3** and **5**).

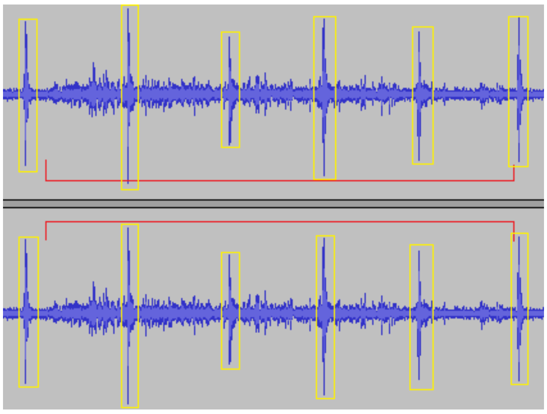

FIGURE 4.2: A full respiration (**inspiration** + **expiration**) where it is possible to see the heart beats (in a yellow rectangle) and the respiration (marked with a red line, with a start and end points).

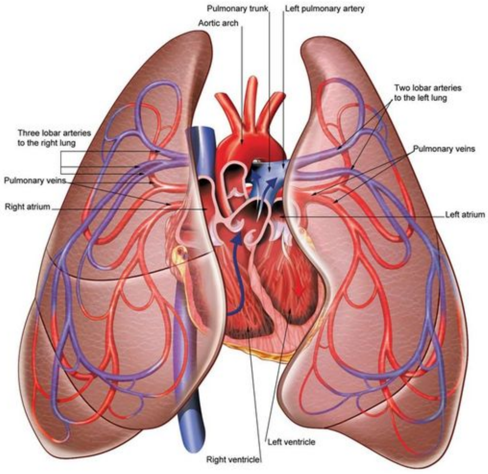

FIGURE 4.3: Human's Anatomy. It is possible to check that the heart is located **behind the left lung**, which means that the audible sounds, when using a stethoscope, have more than just the respiration (**figure 4.2**).

To this end, a series of tests in each position were made to achieve the best results. Those tests consisted in using a first version of the prototype, measuring during **eight** seconds, two times in each position. A **15dB** amplification was applied to every sound so the results could be better visible and audible. It was performed on a healthy subject without any history of respiration problems, lying and facing down (figure 4.7). The results are displayed bellow:

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[1] The image was taken from the following website (accessed on 3/January/2017): http://www.ourtimetolearn.com/blog/wp-content/uploads/2014/09/lung-and-heart.jpg

- **Position 1**

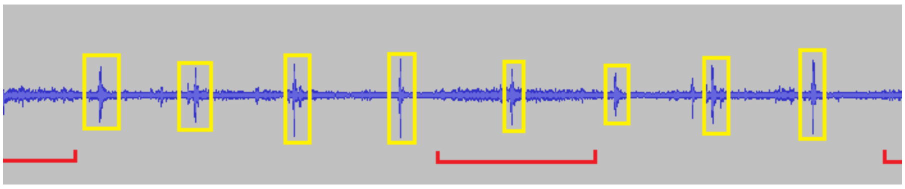

FIGURE 4.4: Sound recorded from position **1**. The yellow rectangle represents the heart beats and the red line (with a start and end points) represents an **inspiration**.

- **Position 3**

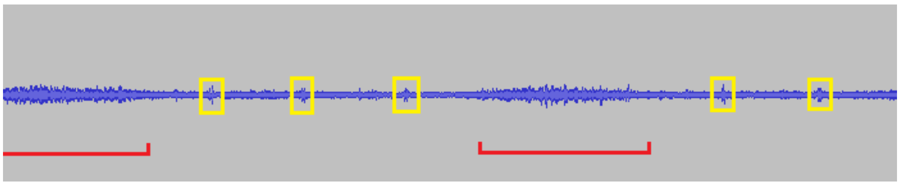

FIGURE 4.5: Sound recorded from position **3**. The yellow rectangle represents the heart beats and the red line (with a start and end points) represents an **inspiration**.

- **Position 5**

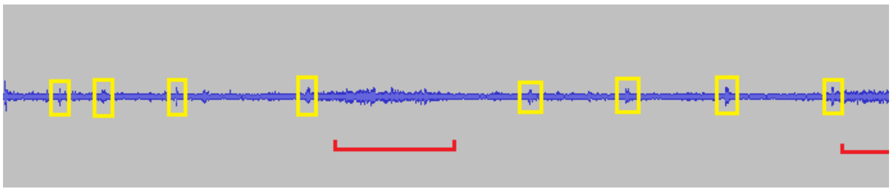

FIGURE 4.6: Sound recorded from position **5**. The yellow rectangle represents the heart beats and the red line (with a start and end points) represents an **inspiration**.

With these results, we can notice that position **3** and **5** provides us with the best sounds. In position 1 (figure 4.4), it is clearly visible that the heart beats are present (with a higher amplitude comparing to the other positions). By looking at figure 4.1a and figure 4.3, we can see that both positions **1** and **2** are near the middle between the two lungs and, because of that, the hearts beats are most likely to be higher in those positions (as proven on figure 4.4). Between position 3 (figure 4.5) and 5 (figure 4.6), the main difference, in this experience, is in the respiration sound; in position 3, the respiration sound is higher and uniform and, on the other hand, in position 5 the respiration sound was more unstable in the two measures.

FIGURE 4.7: Position of the stethoscope on the back of the subject. According to **figure 4.1b**, it is the **third** position.

These are preliminary results that, for this subject, result in a cleaner sound, when auscultating in position 3 and 5. Although both positions had good performances, we will balance the tests and choose position 5 (because it is the best position to capture wheezes) and position 1 (to acquire anterior lung sounds, which are relevant for cough detection).

4.2 Algorithms

In chapter 2 we briefly discussed several algorithms to detect wheezes and cough. The following sections will describe, in detail, both algorithms chosen for the project and the different approaches that algorithms used to achieve the best results. They were developed within our research group and the authors authorized their use in this project.

4.2.1 Wheeze detection using the spectrogram space and musical features

The key for the algorithm to detect wheezes is to use their distinct signature in the spectrogram because those sounds have a musical nature (similar to whistles). There are thirty features within this method that allows to detect wheezes. One of the thirty is by using the signature of the sound (spectrogram). This method works by:

- **Signal filtering** - using the first derivative of the discrete Gaussian kernel;
- **Computation of the spectrogram** - using a flat top window;

- **Subtraction of the background** - subtracting the frequencies values with the background estimation;
- **Peak detection** - using a time frequency analysis;
- **Reduction of false positives** - using morphological opening by reconstruction operator;
- **Computation of the array of weights** - improved by using a temporal Gaussian regularization.

The other twenty-nine features are all musical and were computed using the *MIRtoolbox* [32] (eg., timbre and tonal features).

The collected data was provided by auscultating twelve volunteers at the **General Hospital of Thessaloniki** and **General Hospital of Imathia**, both in Greece. Nine were patients and the other three were healthy subjects; six patients had wheezes or crackles and the healthy subjects had normal respiratory sounds. Using a Littmann 3200, at 4000Hz, and with the volunteers seated, the authors recorded twenty-four sounds (two for each patient, in two different positions, selected from 6 possible, as the ones where the sound was best heard) with a 30 seconds duration. From those recordings, 113 wheezes were found. [17]

Being in an controlled environment (hospitals), the background noise is not present (although they have a specific phase that allows to reduce the noise - subtraction of the background).

Using the Random Forest Classifier, the results of the algorithm were very good, with a sensibility between **86.5%** (using one feature) and **90.9%** (using thirty features) and a specificity between **88.3%** (using one feature) and **99.4%** (using thirty features). The main drawback is the low number of subjects that participated in the collection, which raises questions regarding the generalizability of this study.

4.2.2 Detection of Explosive Cough Events in Audio Recordings by Internal Sound Analysis

Unlike the wheezes detection algorithm, to detect cough they use a set of preprocessing and feature extraction methods. After that, they use the results and pass them to a classifier. In the last version, the classifier used is a Support Vector Machine (SVM) and not the Logistic Regression algorithm.

- To focus only in the segment of the sounds that they want, and to have all the sounds in the same level, the preprocessing transforms the sound to make it possible to only have what it is needed:
  - the audio is filtered with a band-pass filter (at 80Hz and 1000Hz);
  - the resulting audio is filtered again but for silent segments;
  - finally, it returns the cough events that were not discarded.
- Regarding the feature extraction, first, for each event, they compute the magnitude spectrum using the Short-Time Fourier Transform (STFT), divided into 50ms frames. After that, they apply pitch and spectral features:
  - Pitch features - the five features are related to the fundamental frequency (F_0):
    - Pitch coverage (ratio of frames where F_0 is detect and total number of frames in event), mean, median, standard deviation (of F_0) and inharmonicity (ratio of partials that are not multiple of F_0);

- Spectral features - a spectral flux was computed as the Euclidean distance between the magnitude of successive frames. Three features were extracted from the vector:
    - Mean, median and maximum.

In the original paper [26], the authors used a Logistic Regression algorithm from Weka. In a newer version the authors used SVM to adjust the results to return the ones that are above a certain probability (we used 80%) to belong to the class cough.

To calculate the results, it compared four different feature sets: Baseline (comprises 19 features), Proposed (9 features), Combined (28 features - Baseline + Proposed) and Filtered (10 features obtained by classifying the training set, removing the misclassified instances and selecting the best 10 attributes).

The sounds were recorded in **Portugal** and **Greece**, in 46 healthy subjects and 13 patients (they had respiratory diseases). The records were made using a Littmann 3200, with a frequency of 4000Hz. When comparing the different datasets, the results of the Combined set are the best, with a sensitivity of **93.4%** in the Portuguese dataset and **86.0%** in the Greek dataset, and sensibility of **83.4%** in the Portuguese dataset and **71.5%** in the Greek dataset.

The results are not bad and the preprocessing embedded in the algorithm to adjust all the signals at the entrance is an idea that can help to standardize the input and have more reliable results.

4.3 Bluetooth and Wi-Fi

To connect the prototype to a phone/server, we need a piece of hardware that can help with that communication. In **section 2.3**, when comparing the systems, only the **Arduino 101** had an embedded piece that can do that. So, for the other two systems to have the possibility of communicating with the exterior, we need to add the corresponding hardware. But the problem is, which one is the more adequate for our needs: **Bluetooth** or **Wi-Fi**?

There are main differences regarding to Bluetooth and Wi-Fi [33]. Before assuming which one is the best, there are some aspects that matters to this case.

	Bluetooth	**Wi-Fi**
IEEE spec.	802.15.1	802.11a/b/g
Frequency band	**2.4GHz**	**2.4GHz / 5GHz**
Max Signal Rate	1Mb/s	**54Mb/s**
Nominal range	10m	**100m**
Nominal Transmission Power	**0-10dBm**	15-20dBm
Channel Bandwidth	1MHz	**22MHz**

TABLE 4.1: Comparison between Bluetooth and Wi-Fi, regarding to Frequency, Signal Rate, Range, Transmission Power and the Channel Bandwidth [33].

By consulting **table 4.1**, we can assume that Wi-Fi is better than Bluetooth. It can send data further way, with more data in a single transmission. But all of this comes with a cost: the transmission power is higher in Wi-Fi. So, and due to the project characteristics, we need to re-evaluate the values that come with that table. For this analyses, we are going to compare the following parameters: **power consumption** (the project has limited power, so it needs to save energy without unnecessary data transmissions), **range** (depending on the situation it can be close or not from a server that will handle the processing) and the **transmission rate** (no extra data needs to be sent).

- **Power Consumption** - regarding power consumption, Bluetooth has an advantage, costing less **73%** in terms of transmission and **78%** in the reception. With this values, it is clear that Bluetooth costs less. But, in this case, the paper only regards to the first version of Bluetooth. Nowadays, there is a version (Bluetooth 4.0 or Bluetooth LE) that was made to decrease the power consumption, but affecting the amount of data that is sent - it is not meant to have continuous transmission. BLE was made for IoT devices - like Arduino - and it can be powered with a coin cell for a *"long period of time"*[2]. Because the new version of Bluetooth is more efficient than the previous one, it is possible to say that **Bluetooth LE uses less energy than Bluetooth** and, also, **Wi-Fi**, with a loss in the transmission rate (if there are lots of information to be sent)[33].

- **Range** - the main purpose having data collected is to send it to:
  - **Server** - in this case, the data needs to be sent to a server (and then it will be processed to find results) that is far way from the patient. For this situation, the Wi-Fi is better because the protocol was made thinking on long distance communication.
  - **Phone** - for this case, the phone will act "like a server" and it will have all the code running to extract features and analyze the data. The phone will have a battery drain higher than the normal because it will not send data to other servers and, because of that, it will process everything on it.
  - **Phone and Server** - it is the best of the previous two parts. The data is sent to the phone (by **Bluetooth**) and it can be pre-processed; then, it can be sent to a server (by **Wi-Fi**) to complete the data processing;

- **Transmission Rate** - one important aspect to take into count is the transmission rate. In this specific case, the data that is sent from the device to another are an array of numbers that have to be processed. The size of the data sent can be measured depending on the size of the array, so, we can control, in a easy way, the data that is going to be transmitted. Looking at table 4.2, it is possible to notice a huge difference between Bluetooth and Wi-Fi and that is because of the protocol itself - one is made for shorter distances, the other was made for longer distances. In this case, and because we can control the data, there is not need to have a protocol that send data with a higher bit rate - with that, there is a cost in the power consumption too. For this reason, the Bluetooth is the right choice.

	Bluetooth	Wi-Fi
VDD (volt)	1.8	3.3
TX (mA)	57	219
RX (mA)	47	215
Bit rate (Mb/s)	0.72	54

TABLE 4.2: Comparison between the protocols (part of table IV from [33]).

One extra point about this comparison is the difference between both protocols: when we use Wi-Fi, we **need to have an Access Point (AC)** near us, which may not be always the case; on the other hand, the number of phones that exist nowadays (and working) is superior to the world's population, so, in average, there is one phone/mobile device [34] for each person. Assuming that half of the devices have Bluetooth integrated, we are considering that half of the world's population will be able to use our system. This allows for the scalability of the project and the independence of a specific device to use our prototype.

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[2] https://www.bluetooth.com/what-is-bluetooth-technology/how-it-works/low-energy - the website is no longer available, but it is possible to use web.archive.org to obtain an online instance from the website (https://goo.gl/8jSJsB).

With all the comparisons made, there is a clear winner between both: **Bluetooth**. In all the aspects analyzed, Bluetooth fits in every single one. There is not need for higher transmission and reception values and the power consumption is very low in both operations. By choosing Bluetooth, the option is to send data to a phone and then it will be processed there.

On the other hand, the Bluetooth version that was being compared here is an older version, before **Bluetooth 4.0 (Low Energy - LE)** (CurieBLE - Genuino 101 - is Bluetooth 4.0). This version has improved the power consumption (consumes **less** than the previous versions) decreasing on the transmission and reception of data [35] [36], although the rates are acceptable for our prototype. With this kind of protocols available to us, we can opt for a solution **prototype** $\Longleftrightarrow$ **phone** knowing that the power consumption is low, but the data is transmitted normally, without any bumps on the way between the gateways.

4.4 Electronic Components

When talking about electronic components, we are talking about mechanical pieces that can help to modify the signal that can be obtained by the microphone. The main pieces that we are going to focus on are:

- **ADCs** (Analog-to-Digital Converter) - having analog inputs is very useful for collecting data from sensors (microphone in this case) and because the Raspberry Pi does not have an ADC, we need to simulate it by using this converters and connect them to the board. We are going to analyzed the following components:
  - MCP3008;
  - ADS1015.
- **Op-Amps** (Operational Amplifier) - these pieces are fundamental when amplifying signals. They are used to increase the signal by boosting it by a constant. The Op-Amps that are going to be analyzed are:
  - LM324N;
  - LM833N;
  - LM386N;
  - LM358P.
- **Microphone** - with the frequencies of wheezes and cough normally comprised between 100Hz and 1500Hz [37][24][18], we choose a microphone that had those frequencies within its range (by remembering the Nyquist theorem, we also need to take into account that the frequency needs to be, at least, the double of the frequency of the signal, so it must be, at least, 3000Hz):
  - Omni-Directional Foil Electret Condenser Microphone.

4.4.1 MCP3008 (ADC)

The **MCP3008** [38] is a 8-channel, 10-bit analog to digital converter (ADC). It consumes 500 μA (max), but when it is not being used, it will consume only 2 μA. It costs around **2€**.

4.4.2 ADS1015 (ADC)

ADS1015 [39] is a 4-channel, 12-bit analog to digital converter (ADC). It has 2 more levels of signal conversion, so there are less conversion errors when compared with the 10-bit ADC, MCP3008. On the other hand, it has a continuous mode, which means that it is always running and consuming 125 μA. It costs around **9.5€**.

4.4.3 ADCs - Comparison

	MCP3008	**ADS1015**
Resolution	10 bits	**12 bits**
Channels	**8**	4
Max Power Consumption	500 μA	**125 μA**
Stand-by Power Consumption	**2 μA**	125 μA
Costs	**2€**	9.5€

TABLE 4.3: Comparison between the 2 ADCs, regarding to the **Resolution**, **number of Channels**, **Max Power Consumption**, **Stand-by Power Consumption** and the **Cost** of the component.

It is not an easy task to select which one is the best because both have good characteristics. Only by analyzing each factor it is possible to reach a conclusion about them.

- **Resolution** - with 2 more levels of resolution, ADS1015 can have a more clean signal, but the difference between 10 and 12 is not the same as 12 to 14 (because the expression is an exponent of 2 - 2^n, where n is the level). The higher the level of resolution, more detailed is the converted signal but more CPU is used to do that operation;

- **Channels** - with more channels, it is possible to connect more devices. So, if we want to connect more devices, the MCP3008 has twice the numbers of possibilities to do that;

- **Max Power Consumption/Stand-by Power Consumption** - both factors are very important, but there is a great difference between them. The ADS1015 only has one mode: **continuous**. This means that it will constantly consume 125 μA. On the other had, the MCP3008 will consume a maximum of 500 μA, but in stand-by only consumes 2 μA. That is a great difference between both and it will depend one the use; in this case, the use will be mostly continuous with few stand-by moments, making the ADS1015 the appropriated ADC;

- **Costs** - the MCP3008 is five times cheaper than the ADS1015, specially because the resolution and the higher power consumption.

After analyzing step by step each one, and according to the main purpose of these project, the **MCP3008** is the correct one, despite having a higher power consumption (when on **max power**). This will give us a chance to have more than 4 devices connected, with a smaller price.

4.4.4 Op-Amp - Comparison

	Gain	Energy Drain	Cost
LM324N	100dB	700 μA	**0.30€**
LM833N	140db	1 mA	0.80€
LM386N	**200db**	4 mA	1.70€
LM358P	100dB	**500 μA**	0.40€

TABLE 4.4: Comparison between the 4 op-amps, regarding to the **Gain** of the signal, **Energy Drain** and the **Cost** of the component.

By consulting **table 4.4**, it is possible to see that the higher the gain, the higher the cost and the energy drain. The factors presented in the table are determinant for choosing the best Op-Amp for the project:

- **Gain** - The lung sounds are normally associated to a very low sound (i.e. normal respirations) and it needs to be amplified. One issue with this technique is that not only the sound will be amplified, but also the noise that it collected and, because of this, applying a higher gain could not be the best case (the filter for this will be different from a lower gain);
- **Energy Drain** - With a higher gain, higher is the energy consumption. The LM386N consumes four times more than the LM883N, which, in a larger scale, can be very bad. Although the energy units are very small, one of the objectives of the project is to be wearable and for a long time usage, so consume less energy is better;
- **Cost** - The prices are not very high and despite the costs of the LM386N being higher than the others, the gain that it can produce compensates the higher price.

Without having any tests to prove which kind of amplification we need, it is not possible to decide which Op-Amp we need for the project. Furthermore, when the prototype is being done, more details about this section **will be revealed after the first results become available**. Even without any chosen op-amp, **NFR10** is satisfied.

4.4.5 Microphone

The chosen microphone [40] has a range from **100Hz to 10000Hz** [41], but because the sound suffers amplification from the stethoscope's head, the minimal range is acceptable for detecting adventitious sounds. It is **very small** and it fits inside the stethoscope head (the DM130); the power consumption of the device is small (**0.5mA**) when running at full power. It costs **0.9€**, being very cheap.

4.5 Architecture

The aim of this section is to show the architecture behind the system and the prototype. Starting with a system overview, we will show how the original architecture was with all the steps represented in the scheme. Afterwards, we will discuss the three embedded systems and choose the one that we are going to use in the project.

4.5.1 System

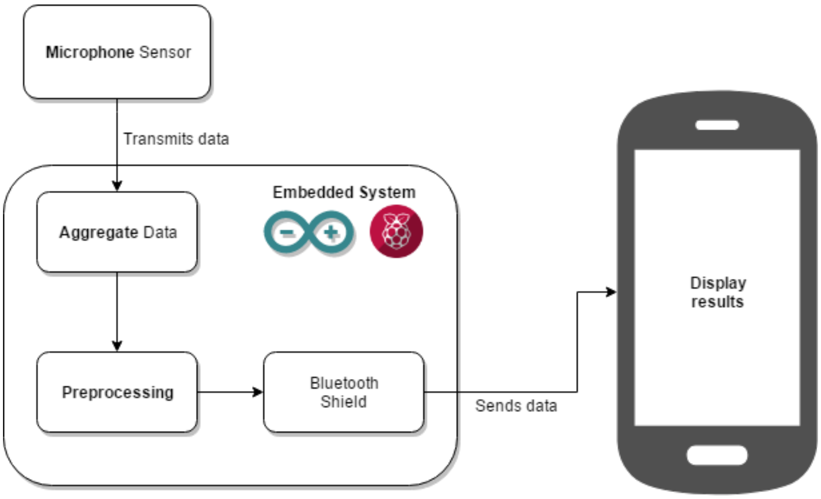

FIGURE 4.8: System's architecture with the various steps from the data gathering to display results.

In **figure 4.8** a diagram of the system is provided. The main idea is to have a microphone transmitting data to the embedded system. It will aggregate the data, preproccess it and send it throughout Bluetooth to a nearby device, in real time.

4.5.2 Prototype

This chapter shows three different prototypes for each embedded system studied. In the three cases it is only displayed the board and the necessary components to collect data, and not the wireless communications modules needed (for the Lilypad and for the Raspberry Pi Zero), neither the mechanical head where the microphone will be inserted and the power supply. The prototypes were built using **Fritzing**[42], an open-source software that allows to create hardware in a simple and easier way.

- **Arduino Lilypad USB** - the circuit is very easy to build and it only needs a 10kΩ resistor to be added to the circuit, to detect changes on the voltages (it is read in the A2 port of the Lilypad). To send data to other devices, a Bluetooth module (normally, when we use Lilypad as the main board, we use the SparkFun Bluetooth Mate Gold [43]) needs to be added to the circuit.

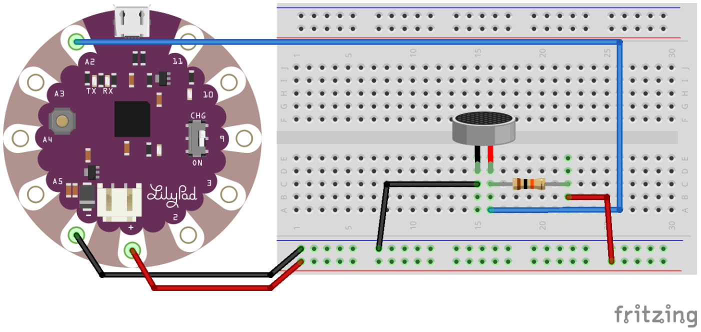

FIGURE 4.9: Arduino Lilypad USB prototype.

- **Raspberry Pi Zero** - after discussing the differences between the systems in **section 2.3**, we know that, for this system, an extra component to provide analog ports was needed. In section 4.4.2 we discussed the different components that can be used for that and we chose the MCP3008. The final diagram is displayed in figure 4.10, without the Bluetooth module (in this case, the best module is [44]).

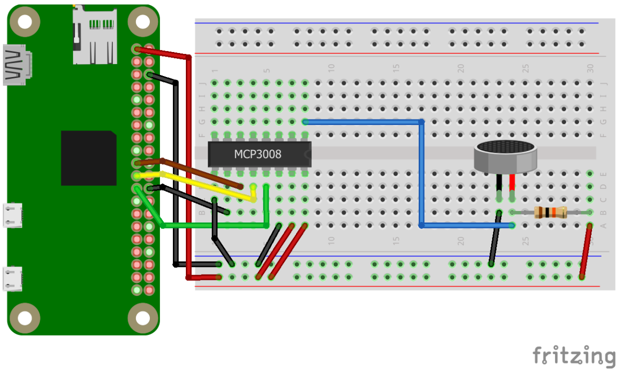

FIGURE 4.10: Raspberry Pi Zero prototype.

- **Genuino 101** - the circuit is similar to the Arduino Lilypad, but the board is more powerful and it already has Bluetooth integrated, so the diagram that is in **figure 4.11** is the necessary for the sound acquisition and data transferring between the prototype and a nearby device (with Bluetooth).

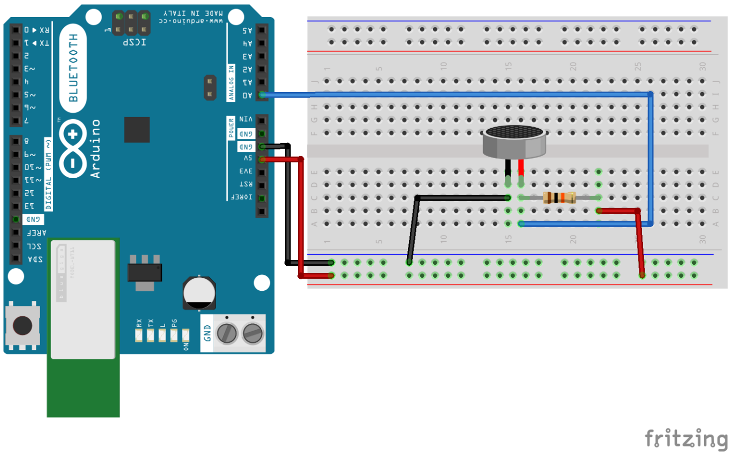

FIGURE 4.11: Genuino 101 prototype.

4.5.3 Discussion

Despite the similarities between the Genuino and Lilypad architectures, both boards have completely different specifications. The Raspberry Pi needs to have the extra component, discussed in section 2.3.2. Only looking at the boards (without any kind of circuit), the Lilypad will have a lower power consumption, but the board does not allow any kind of operation regarding real-time process and high frequency data gathering, making it infeasible for the project. We are to compare the Raspberry and the Genuino, side-by-side, according to four parameters: cost, wearability, circuit complexity and power consumption.

- Cost - the final table in section 2.3 reflects the difference between both devices, with price of the Genuino being six times (almost 30€ against the 5€ of the Raspberry) higher than the Raspberry.
- Wearability - Genuino is bigger, but the difference is not so significant (i.e. it is possible to use the device inside a small box that is hidden in the pockets or attached to the belt).
- Circuit Complexity - Raspberry needs more components to achieve the goal for the project. It needs more wiring and it means that the signal quality will be lower than the Genuino.
- Power Consumption - With more components and a microprocessor (which means that it will run an OS, even without any interface), Raspberry will consume more energy. Even with an embedded Bluetooth sensor, the Genuino will allow for a longer use.

With that said, we chose Genuino 101 and, despite the higher cost, the wearability, complexity, power consumption and the embedded Bluetooth sensor make the device more suitable to the project.

To test the boards and the prototype, we divided the test into two different phases: microphone embedded in the stethoscope head connected to the computer (phase 1) and connected to the systems (phase 2):

- **Phase 1** - in this phase, the prototype was connected to the computer. The software used on the computer was **Audacity** and the tests were made in a healthy subject just to prove the concept of the prototype (the mechanical amplification of the stethoscope head helps improving the sound quality);
- **Phase 2** - the second phase involved connecting the microphone to the embedded systems. The tests were made differently from the first phase, where the only thing tested was if the device could handle multiple samples per second or not. Other difference is in the data that is collected: because the data collected by Audacity is provided by the sound board of the computer, the data is already processed; in the case of the boards, there are in a scale $[0, 1024[$, that is converted to voltage (0 to 3.3V or 5.0V, depending on the voltage of the device). More tests (converting the data to frequency, etc.) need to be done to accomplish the objective of having an embedded gathering and sending data to an external device.

These tests allowed to understand if the chosen board could handle with a huge data acquisition; they did not had any upgrade to amplify the sound captured or to send data anywhere else. Also, in the first phase the microphone was connected to the computer and the data was gathered by Audacity, which means that the sound is processed differently when compared to the boards.

4.6 Remarks

In this chapter we reviewed the several positions to auscultate, the chosen algorithms to detect wheezes and cough, discussed the different components to achieve the objective (microphone, op-amps, among others) and compared between Bluetooth and Wi-Fi and the different architectures for the system and the prototype.

- Regarding the positions to auscultate, we decided to go for two positions: one in the anterior part and other in the posterior part. This allows to get two different measures and see if there are any differences between measuring in the front or in the back.
- The algorithms chosen were developed by our research group; the results obtained where good and the fact that they are recent helps to test the recent technology with recent algorithms.
- The best protocol to use for wireless communications was Bluetooth because the idea is to send the data to a nearby device that can handle the data and, if needed, send it elsewhere.
- We defined the components that we are going to use: microphone, operational amplifier and ADCs (discarded after analyzing the embedded systems).
- We decided which embedded system was suitable for our project.

With everything settled, we can start the tests and check if there are problems and solved them.

Chapter 5

Experiments

During the experiments there were several constraints that needed to be solved, so the project could continue and get the results. Two of the main issues were data transmission and wearability, where we tried to achieve a solution that could be used without having to be connected by cable elsewhere; unfortunately that was not possible.

With that said, the aim of this chapter is to present all the the tests made and the solution for the various constraints found in the way.

5.1 Prototype

Building the prototype involved the construction and testing of several different prototype versions. In total, three versions were built but only one presented acceptable results. We are gong to described them by explaining what and why they failed. As in section 4.5, we will use the Fritzing software to construct the different versions.

Figure 5.1 shows this was the simplest version, and the ideal one, where there was the Arduino connected to a 10k resistor and the microphone. This circuit was very simple, but the results that we got were a very low sound that did not achieve what we wanted.

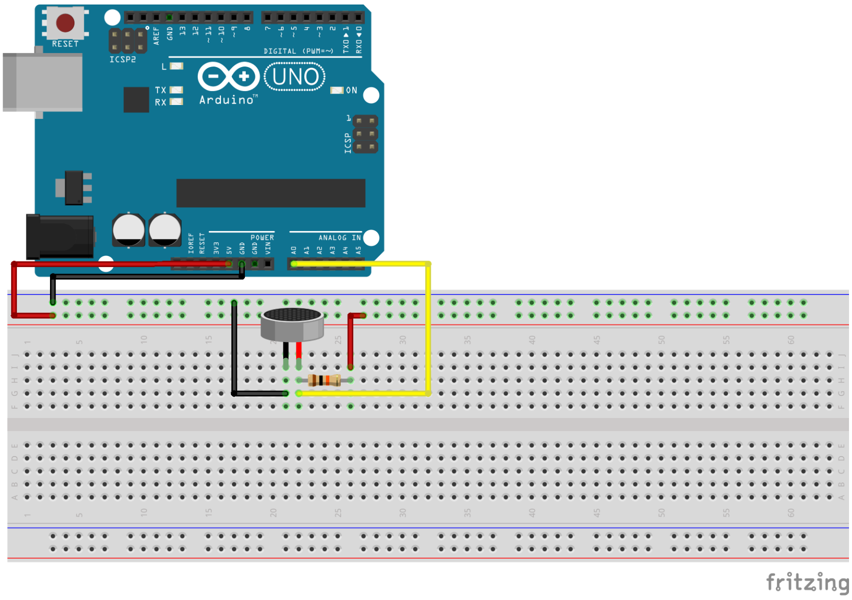

FIGURE 5.1: First version of the prototype.

What was missing in this build was an amplifier; for that reason, we rebuilt it and got the second version (figure 5.2). A more complicated circuit, but the sound was amplified as we wanted.

After deeply testing the prototype we found that the amplified sound was full of white noise and, because of that, destroyed the sounds that we wanted to ear (the noise had high amplitudes).

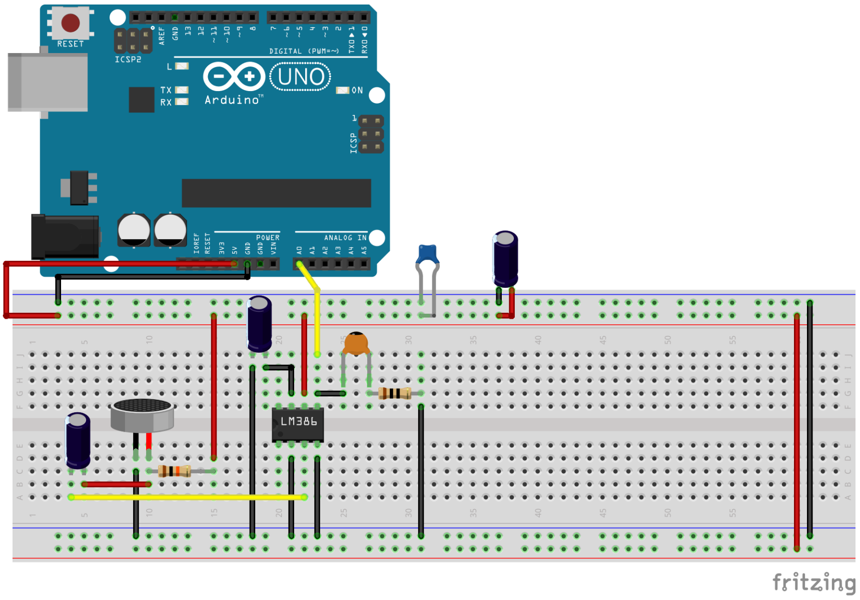

FIGURE 5.2: Second version of the prototype.

There was a possibility to increase 4x the sound by connecting pin 1 to 8, using a capacitor, of the amplifier, but if with a lower increase (without the connection it increased 2x) we had problems, increasing 4x would be worst. The main problem with this circuit is by using the the LM386 amplifier. It is not specific for amplifying audio from a microphone (but for a speaker it could be better). After researching for other solutions, we found an Electret Microphone Breakout[1] that, with some changes, could fit in the project. It has an audio amplifier specially dedicated to amplify audio and it combines everything in a smaller board (figure 5.3).

Although this new version works well, the sound is still low, but there is a great difference between the first one and this: to get higher amplitudes, the person needed to knock harder on table, scream, to increase the volume; with this third circuit, using a voltage of 3.3V, we could get good results without having to make people force a higher volume (the built-in circuits help to improve this), although very lower sounds could not be captured. With this, we can start the tests and, because the circuit is small and does have any resistor or capacitor added to it, the construction does not take long and it is easy to transport from one place to another, in a small box. This final version satisfies the requirement NFR1 because of its simpleness and NFR10 because of the audio amplifier embedded in the microphone breakout.

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[1] https://www.sparkfun.com/products/12758 - Accessed: 24/05/2017

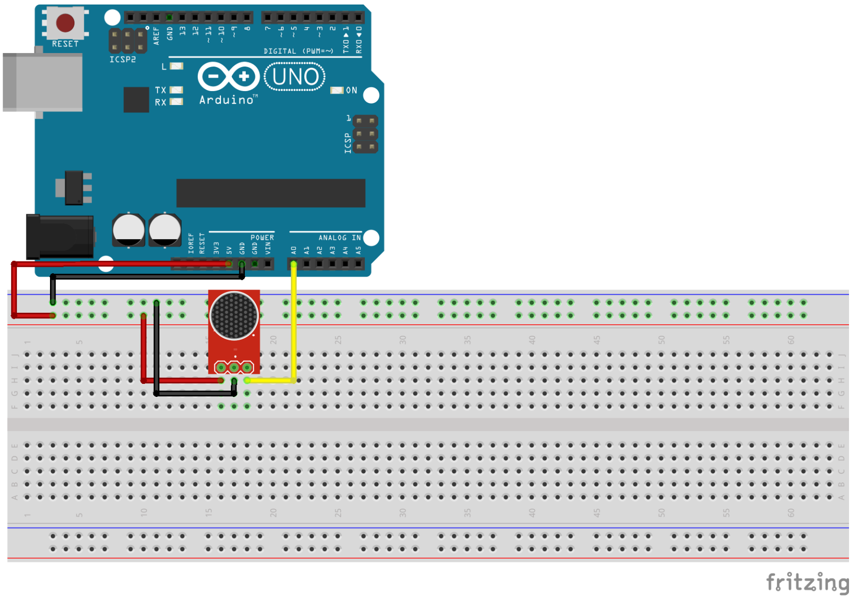

FIGURE 5.3: Third version of the prototype.

With all these changes and knowing that we cannot use wireless data transmission (chapter 5.3), the architecture of the system changed (figure 5.4). The phone is now a computer, the connection is made using a USB cable and the processing is now made directly from MatLab and the results are stored locally. This version does not validate nor either NFR10 or NFR11.

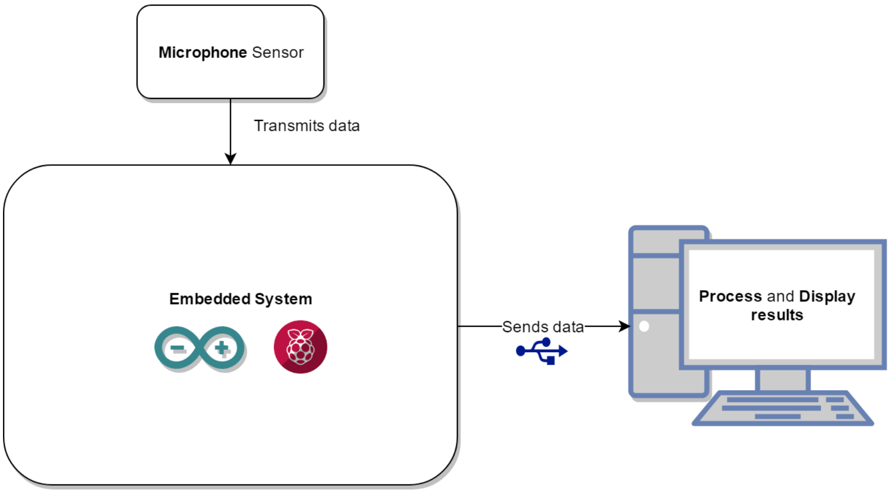

FIGURE 5.4: Final version of the system's architecture.

After building everything we obtained the prototype shown in figure 5.5. We built the circuits for the Genuino 101, but the board had some problems during some o the tests made in a earlier stage. Because of that, we changed the board and used the Arduino Mega because it was the most similar board that we had that could help us to continue the tests. This board does not have any wireless data transmission, but that was not going to be used, as we are going to see.

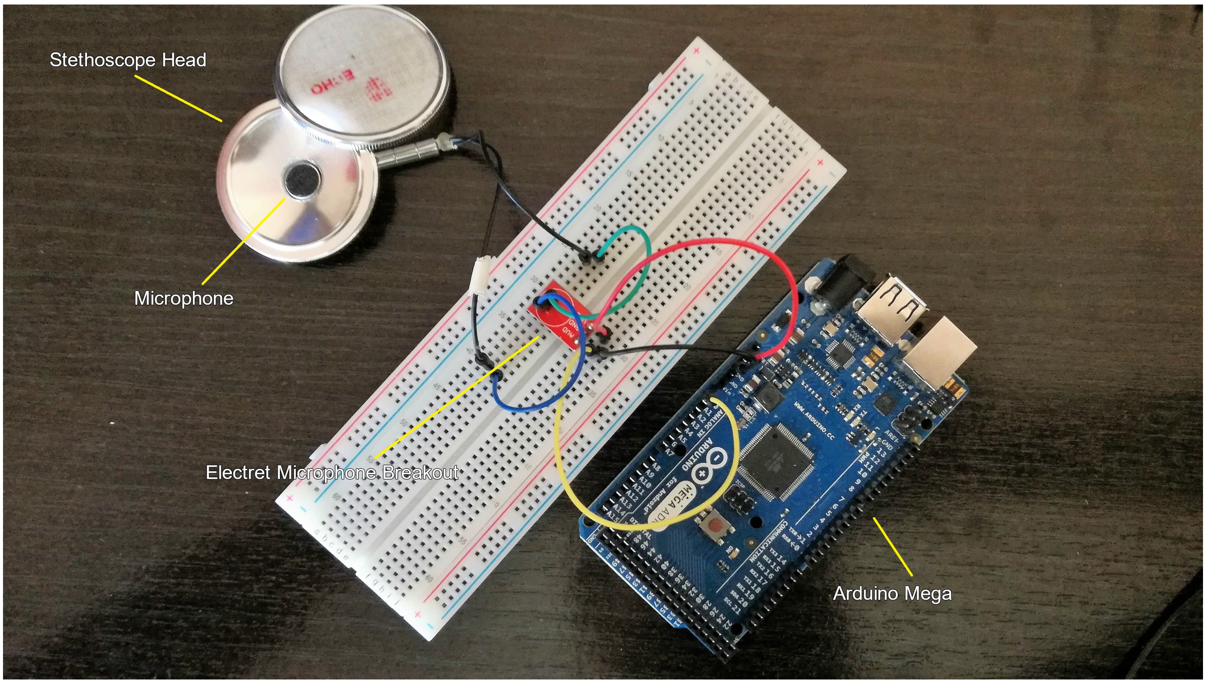

FIGURE 5.5: Real version of the prototype using a microphone embedded in a stethoscope head, connected to a microphone breakout and to an Arduino Mega.

5.2 Experimentation

Before doing the tests, a protocol and a declaration were made to ensure the correct, formal and legal way to obtain the data. Also, the methods for testing were defined. Unfortunately, before, during and after the tests we encountered plenty of problems that needed to be fixed, like the transmission of data, the way to measure in both male and female subjects, quality of sound, among others.

This section describes the tests themselves, since the population, conditions and how the measurements were affected by different constraints (clothes, sex, measurement device).

5.2.1 Subjects and Tests

For the tests, data was collected from 20 subjects, 16 male and 6 female, between 19 and 49 years[2] old. From the 20 subjects, 19 do not smoke and never smoked and more than 50% practices exercise one or more days per week. The lowest BMI was 19.1 and the highest 30.5, with an average of 23.63. A copy of the Declaration and the Protocol used to make the tests are available in the Appendix B and Appendix C, respectively.

A total of 6 tests were made to every subject: 3 in the anterior part (normal breathing, cough and deep breathing) and 3 in the posterior part (normal breathing, cough and deep breathing). The duration was 15s for each test.

5.2.2 Tests Conditions

19 tests were recorded in the Department of Informatics Engineering, University of Coimbra. Although the room was not full enclosed and the isolation was not perfect, in any case there was no influence (noise perturbation) from the outside that could interfere with the data collection[3].

The subjects were sited and, depending on the sex and the mode (Littmann or prototype), the anterior tests could be done with clothes on:

- **Male** - if the subject brought a shirt, the tests were made with the shirt opened (in the anterior part) and with the shirt over the device (when the tests were with the prototype) or with the shirt raised (with the Littmann) in the posterior part. If the subject brought anything that could not be opened, they took the piece of clothing off for the anterior part tests.
- **Female** - 5 of the 6 female subjects used a top, which allowed a better and easy way to collect the data; but with all the 6 subjects the measurements were the same: the anterior tests were made normally, above the right breast, and the posterior tests were made with the shirt over the device (when the tests were with the prototype) or with the shirt slightly raised (with the Littmann).

On 4 of the 20 subjects it was not possible to collect the sounds from the anterior part (with the prototype) due to the abdominal hair that the subjects had.

5.2.3 Measurements Methods

Although we tried to use the same methods to collect sounds with both the Littmann and the prototype, it was impossible to have the exact same methods for them. With that said, we tested following the next steps:

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[2] The average age was 25 years old.

[3] The only interference that occurred was the malfunction of the devices that did not record properly

- **Littmann** - the stethoscope was hold in both anterior and posterior tests (as it is shown in figures 5.6 and 5.7). The transmission of data was made between a computer with a Bluetooth dongle from Littmann[4] and, in the computer, the signal was converted to a .wav file, applying a diaphragm filter, using the Littmann StethAssist Sofware.

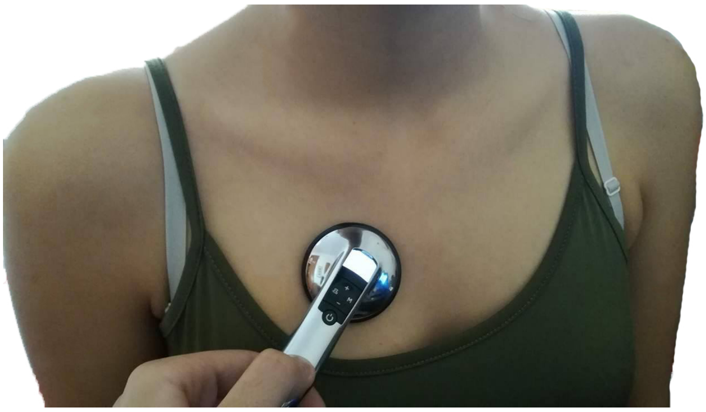

FIGURE 5.6: Test on the anterior part, using the Littmann Stethoscope.

FIGURE 5.7: Test on the posterior part, using the Littmann Stethoscope.

- **Prototype** - the stethoscope was attached to the body with a medical tape (as it is shown on figure 5.8 and 5.9). Unlike the tests made with the Littmann, in these cases there was no contact between the stethoscope and the person controlling the tests, minimizing the noise, and, also, the tests on the posterior part, were made by having the clothing over the device (figure 5.9). Regarding the data transmission, the prototype was connected to a computer using an USB cable and the data was collected by copying and pasting them from a console to a .txt file. Then, using MatLab, we convert the .txt file to a .wav file and stored it.

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[4] https://www.mystethoscope.ca/3m-littmann-electronic-stethoscope-dongle-for-bluetooth-connect/

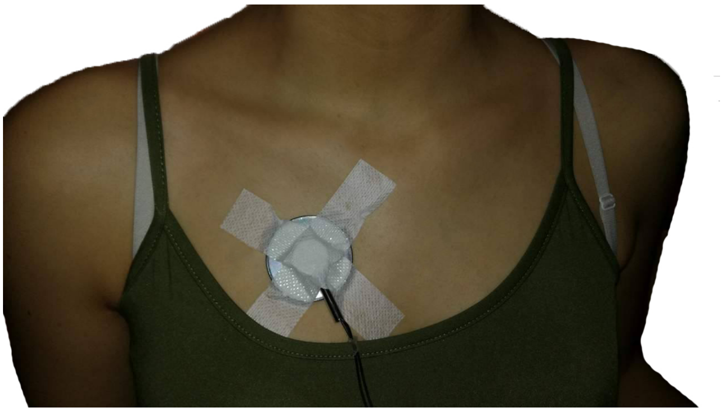

FIGURE 5.8: Test on the anterior part, using the Prototype.

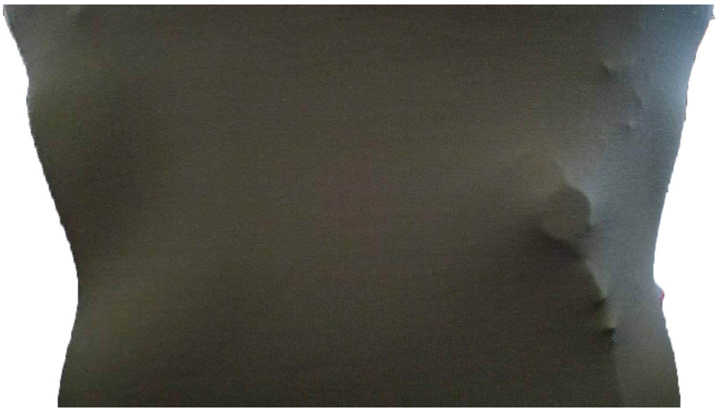

FIGURE 5.9: Test on the posterior part, using the Prototype.

5.2.4 Remarks

We saw how the tests were made and described the population. One of the topics was regarded to transmission of the data from the device to a third party hardware as a computer or cellphone; by recurring to the bibliography and by testing some components, we decided to set the transmission of data by cable, connecting to a computer, and stored them there. This solution affects the wearability but it was necessary to achieve the best results (i.e. higher frequency of the data). The following sections refer these problems of data transmission and wearability.

5.3 Data transmission

Transmitting the data from the Prototype to a mobile phone/computer through Wi-Fi or Bluetooth was one of the possibilities, but it could not be possible to do that. After that, we decided to test by storing the data in an SD card, but it also failed. At the end, the data was collected by copying and pasting the values from a console to a text file. We are going to separate the methods to explain them in detail and separately.

The idea is to achieve the highest sampling frequency possible, to be able to get as much information as we can.

5.3.1 Wi-Fi and Bluetooth

Wireless communications are a plus in every project related to embedded systems and this can allow to interact with the Internet or nearby devices. Although we made a study to compare Wi-Fi an Bluetooth, this actually could not be implemented in the project for some specific reasons.

Starting with Bluetooth, we said that it wastes less energy and it could be sufficient to send data one place to another (locally). Unfortunately, transmitting 3500 samples per second via Bluetooth, in real-time, is not possible using low power protocols. Comparing the two major Bluetooth versions we can check that:

- **Bluetooth 3.0** for allows a transmission of 24 Mb/s, being enough for the data that we want to transmit; but if we want to communicate in real-time, having the data flowing in every clock tick will make the communication inefficient and increasing the battery drain.
- **Bluetooth 4.0** (which includes the Bluetooth LE profile) is, nowadays, a common version used in embedded systems, cellphones, among other devices. It does not consume energy like the previous version, but the range and the data throughput are lower (0.27 Mb/s). Like in the previous version, the bottleneck would be related to the real-time data transmission and, because of the lower data throughput, this version is not good for devices that demand high data rates or constant data transmission[45].

In both versions, when considering the possibility of having a wearable device, we need to have a phone or an electronic device always near it. Bluetooth has a short range (it was designed for PANs - Personal Area Networks) but it is what the mobile phones have nowadays; normally, people take their phone with them and ensuring that the communication is not disrupted is easier than the Wi-Fi (as it is explained next). So, having decided not to use Bluetooth, we decided to check Wi-Fi but it also brings some problems:

- It is a heavy protocol with plenty of features such has range, data transmission, frequency ranges, among others. It will also drain battery quicker than Bluetooth when used to constant transmission.
- To setup a Wi-Fi communication, we need to have an infrastructure built: Access Points (AP) near the device and ensure that, if the device is wearable, we can always have an AP that our device can connect to and, consequently, communicate over the Internet. This is different compared with the Bluetooth because we cannot take the Internet with us like we take our phone.
- In situations that a certain AP is overloaded, we can have problems in the network and it will be impossible to connect any device to the Internet.

Although we studied both Wi-Fi and Bluetooth in previous stage of the project, after starting the tests, both had to discarded and we had to use a cable to connect the prototype to a computer, discarding, also, the possibility of wearability.

5.3.2 SD Card

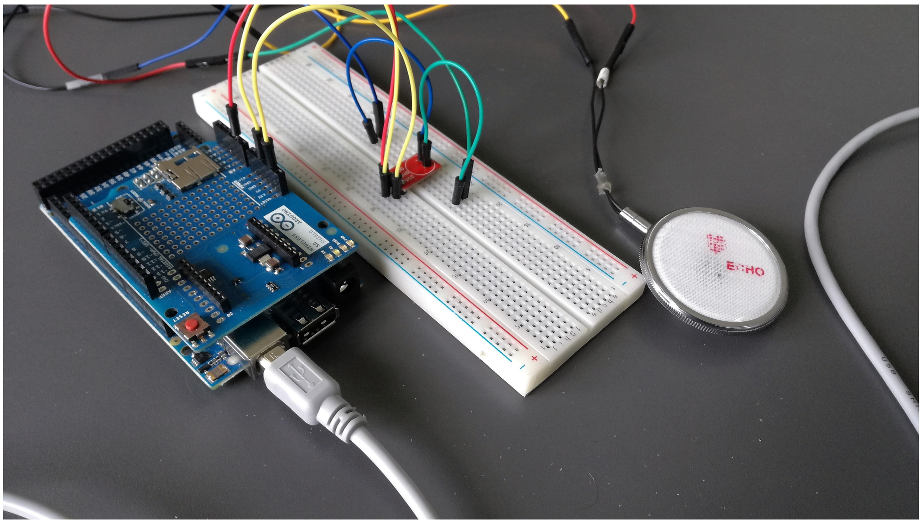

FIGURE 5.10: SD Card Shield mounted in an Arduino Mega.

With the code modified to support writing to an SD card we made some tests to determine the frequency of the sounds recorded.

- On average, the frequency of the sound was **2704Hz** - much lower than the 3552Hz obtained by using the method of copying the values from the console. This is due to the fact that handling mass storage I/O operations on a file system requires a great deal from the MCU. Besides, the heavy usage of interrupts may introduce some jitter in the sampling rate.
- During the tests, the values oscillated between 40000 samples and 180000 samples (4x more), in 15 seconds, which led to a confusion. After some research we noticed that the Arduino was constantly pushing new values to the SD Card (that is the normal behavior) and, if we did not erase the file (in the computer) created by the code, the Arduino appended the new values to the file and, suddenly, there were 180000 samples. After figuring that out, we rose the delay between 2 consecutive writings and the final value for the frequency, using an SD Card, is **2700Hz**.

Since the maximum frequency of wheezes is 1500Hz (according to [18]), and considering the Nyquist theorem, ideally we would need a minimum frequency of 3000Hz. So, for this reason, this is a limitation of this method and we cannot use it. Also, because we want to achieve a frequency that is near the frequency of the Littmann (4000Hz), this value is 32% less, being, also, a limitation.

5.3.3 Remarks

After studying and testing Wi-Fi, Bluetooth and SD Card, we conclude that:

- with the Wi-Fi and Bluetooth, we have plenty of problems regarding constant communication, infrastructure, data throughput. We decided not to use them because none of them would fit within the project scope.
- with the SD Card, the frequency is not sufficient to satisfy the Nyquist theorem and it has a 32% less frequency than the Littmann.

With that, we decided to use the simplest method: connecting to a computer and having the values being dumped directly to it. This affects the wearability and, consequently, does not validate NFR05, as we are going to discuss in the next section.

5.4 Wearability

One of the objectives was to try to make a prototype that could be wearable. With the advances/progresses in the development of the prototype, that objective became more difficult and, before the tests, it was discarded. Because of that, having a device that can, autonomously, store and process is not possible.

Despite that, there were some positive aspects to take into account. By looking at figures 5.8 and 5.9, in contrast with the figures 5.6 and 5.7, we can see that the prototype is not being held by anyone but with a medical tape. By not having anyone holding the device, a person can walk and use it longer. The program inside the prototype runs by itself, without a need of having buttons/switches to turn it on. The requirement NFR01 is partially fulfilled because it will be evaluated by the subjects that are going to test it, but the complexity of the prototype is simple and does not need extra components to start working.

This is a positive point regarding wearability, but this does not mean that quality of the recorded sound is good. In the next chapter we are going to process and analyze data, based on some parameters, regarding to its quality. This will help reaching better results and show if there is significant differences between the sounds collected by both devices (i.e. the Littmann and the prototype).

5.5 Sound Quality

Despite all the precautions with the electronic isolation, wire's length and electronic signal losses, the sound quality is one of the main concerns regarding the validation of the prototype. For that reason, a simple algorithm was used to determine, based on some parameters (described bellow), if the signal was good. To get the signal quality, a set of four parameters had to be configured, such as:

- **thrSil** - Threshold from which the sound is considered silence (measured by the amplitude, in percentage);
  - Comparing the amplitudes from the Littmann with the Prototype is not an easy work, specially because the amplitudes from the Prototype are very low, as it is possible to see on figure 5.11. All the sounds collected by the Prototype have these similarities and, with that, this parameter needs to have a low value to be possible to accept sounds from our build.

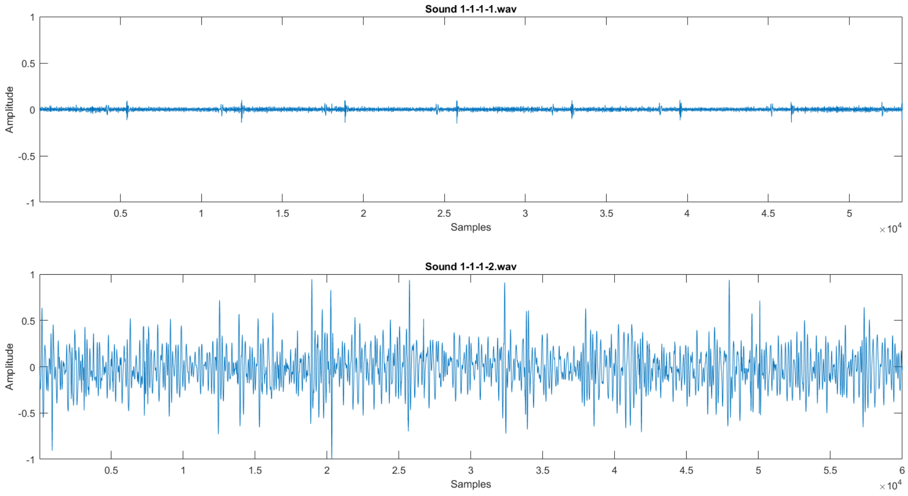

FIGURE 5.11: Amplitude comparison between the Littmann and the Prototype.

  - We choose 1.5%. Higher than this, most of the sounds will be discarded or have very low percentage of useful parts (it also depends on the **silLen**).
- **thrSat** - Threshold from which the sound is considered saturated (measured by the amplitude, in percentage);
  - After analyzing the sounds collected, we choose 50% to be the value for this parameter. Our records do not have plenty of saturation, except when there is a cough; in that case, the sign will saturate during the duration of the cough. The value reflects exactly that and, in combination with **satLen**, it will not discard the cough/wheezes, but other values that are not what we want. Looking at 5.12 we can check that the prototype saturates short after 0.5 and -0.5, but because the value **satLen** is defined to catch certain durations, cough values are not affected.

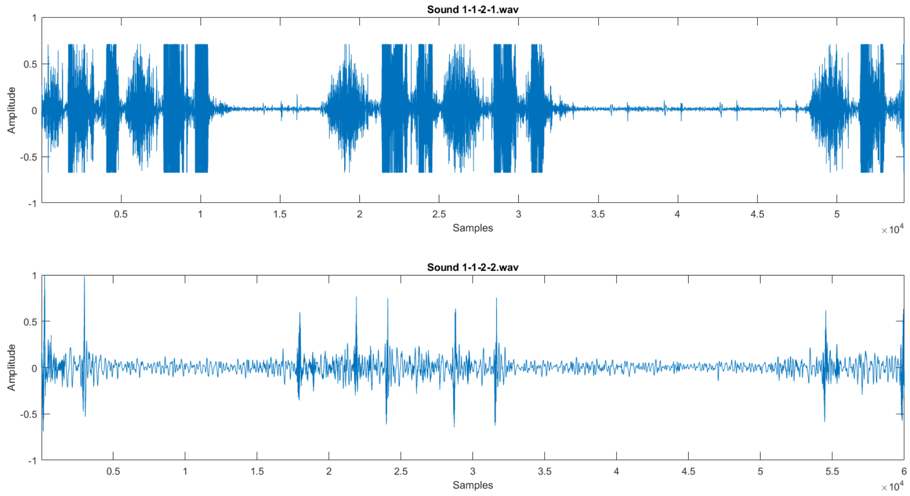

FIGURE 5.12: Amplitude comparison between the Littmann and the Prototype (for cough).

- **silLen** - Minimum duration which the silent segment starts to be discarded (in seconds);
  - If we catch a sample bellow the threshold, we need to check if the next samples are also below that threshold. But, we need to specify a value that indicates if there is plenty of silence so that part of the sound can be considered bad.
  - For this value we choose 0.5 seconds.
- **satLen** - Minimum duration which the saturated segment starts to be discarded (in seconds);
  - Very similar to **silLen**, but will be applied to the saturation. For this situation we need to take into account mostly the cough. Normally a person needs to perform a deep inspiration followed by the cough (or vice-versa if the person cough first) and the time to perform those actions vary from person to person (looking at figure 5.12, Sound 1-1-2-1.wav, it is possible to check that before the saturated signal - the parts where it has a straight line - there is a signal that represents the inspiration before the cough).
  - Because the tests did not demand a continuous cough, we choose 1.5 seconds for this parameter.

With the parameters defined, we also defined the minimum percentage that we consider for a sound to be accepted for the following analysis. With the tests duration being 15 seconds, we considered that sounds with **90%** (13.5 seconds) or more quality are acceptable for the analysis. Figure 5.13 shows the results for the parameters defined previously.

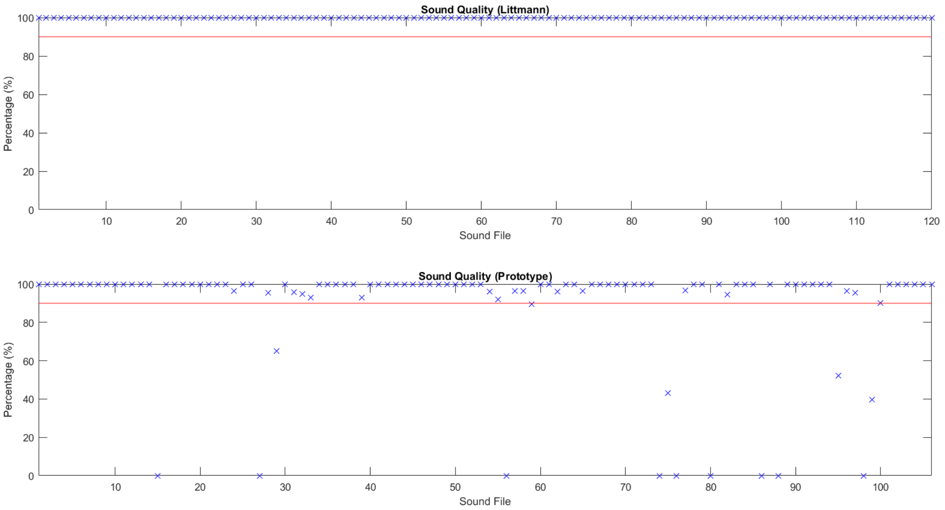

FIGURE 5.13: Sound quality comparison between the Littmann and the Prototype. The red line is the 90% mark.

There is a great difference between the Littmann and the Prototype. All the 120 Littmann sounds were considered acceptable with 100% of quality, which is very good, but not surprising. The Littmann has filters and amplifiers that will make the sound to be loud and clear (not saturated); also, the threshold for silence was very low so it could be possible to have acceptable results from the Prototype (that does not have have amplifiers and filters); if the threshold of silence (**thrSil**) was slightly higher (10%), the results would be very different and there was only one acceptable record from the Prototype (figure 5.14).

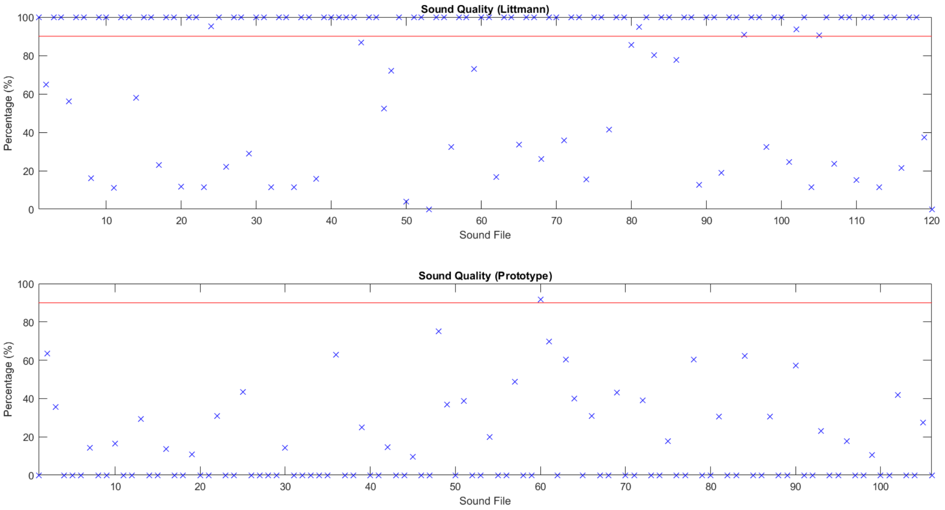

FIGURE 5.14: Sound quality comparison between the Littmann and the Prototype, with higher **thrSil**. The red line is the 90% mark.

Regarding figure 5.13, the Prototype did not achieve so good results compared with the Littmann, but there are some aspects that we need to mention:

- 14 of the 106 sounds recorded were bellow the 90% mark, with 9 having a quality of 0%.

- 3 of the 14 sounds discarded were measured on the posterior part and the 3 were normals respirations.
- 2 of the 14 sounds discarded were cough measures.
- 7 of the 14 sounds discarded were normal respirations in the anterior part.
- 2 of the 14 sounds discarded were deep respirations in the anterior part.
- 11 of the 14 sounds discarded were recorded on the anterior part.
- 6 (3+3) of the 14 sounds discarded were from two subjects.

13.2% of the recorded sounds were discarded, but most of them were recorded on the anterior part and with normal respirations (the algorithm considered that 100% of the sound was silent), meaning that normal respirations are not totally audible with the prototype.

One aspect that is also important is the sample rate (fs) of the sounds. The Littmann has a steady fs of 4000Hz, where, every sample is collected exactly every 1/4000s (0.00025s) and, consequently, all the Littmann tests have exactly 60000 samples (corresponding to the $15 seconds * 4000 samples/second$). On the other, the fs of the prototype is not constant and it varies between 53273 to 55851 samples/sound, 3551 to 3723 samples/second (a difference of 2578 samples/-sound). This is a huge difference between the prototype and Littmann, but also within the prototype measurements. There are several reasons that explain this fact and can help us understand why this different exists.

- Between Littmann and Prototype - the Littmann is built with specific components constructed for it and the recoding and Bluetooth devices that it has are more powerful and effective than a combination of existent components (as our prototype).
- Our board works with variable bit rate, meaning that writing a 0 (uses 4 bits) is quicker than writing 16 (uses 8 bits), and the lower it is the value to be written, the quicker it will be. So, in normal and deep respirations sounds the amplitude does not oscillate much, being the mean value 350 (12 bits to represent the value), but in the cough sounds, the signal saturates and the amplitude reaches the maximum (720 - it takes also 12 to represent the value) and the minimum (0 - has we saw, it only takes 4 bits to represent). So, for normal and deep respiration sounds we have 12 bits being written (one set after the other), but during cough events we can have 3 times more values (if they are compressed between 0 and 15), meaning that, within the same 15 seconds test, we can have more samples when the values to be written are lower than 16. For this reason, the cough sounds have a higher frequency than the other two tests.

The sound provided by the prototype is not the best and this is possible to see it by looking at the results of the quality test and the analysis of the sample rate of the collected sounds. We maintained the highest fs possible (validating partially NFR08) to be closer to the fs of the Littmann but, in contrast, the sound provided by the microphone has significantly lower quality when compared with the Littmann, making NFR09 not validated.

5.6 Results and Statistics

The main purpose was to study if it was possible to detect wheezes using embedded systems, but because we only had 1 subject with wheezes, we start studying the detection of cough. Despite that, we will focus the attention on both problems, but emphasizing more on the cough. The test results can be found in Appendix D (Littmann Results) and Appendix E (Prototype Results).

5.6.1 Cough

To analyze cough we used the algorithm described in [26], where the results were the events where a cough occurs. In our case, we consider a positive value when the algorithm detects an event of cough correctly; otherwise, it is a false positive. For a specific example, the algorithm returns 4 cough events (the consecutive red lines show the beginning and the end of a cough event, figure 5.15).

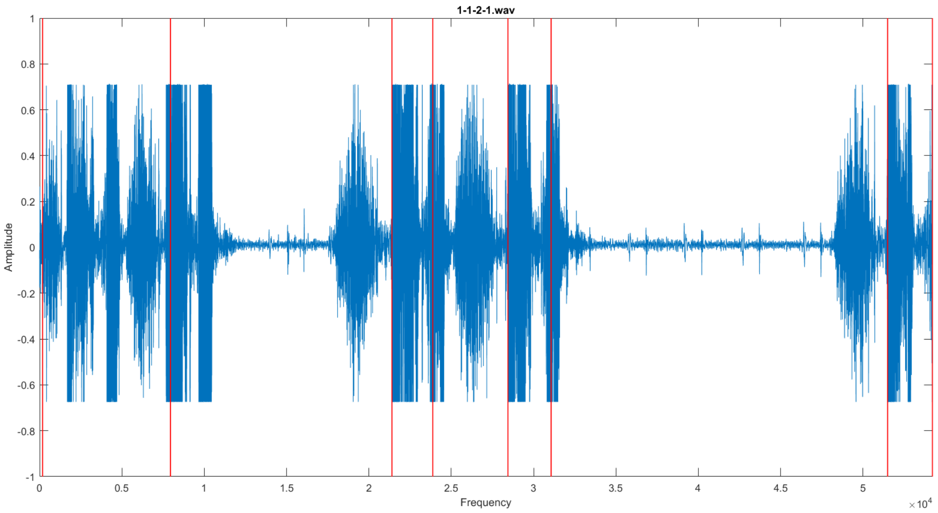

FIGURE 5.15: Cough events represented by horizontal red lines (pair).

By looking at the figure, we see that there are incoherences between the events (i.e. not detecting a full cough event, detecting or not the inspiration part). To guarantee that all the signals are treated equally, we consider the following aspects:

- Unlike the algorithm, we want detect if a certain section of a sound file was a cough event, and not only part of it. For that, we analyzed sample by sample and if the algorithm detects an event, but does not get the full event, we consider, the highest value before the event finishes, manually (the algorithm, sometimes, does not return the full events, missing some samples of it, like in figure 5.15; then, the red lines, that determine the end of the event, are moved to the latest highest point in the event, green lines, figure 5.16). With this configuration, the line 1 will be in the position of line 2, line 3 to line 4 and line 5 to line 6, getting all the samples that are within the event and never over it.

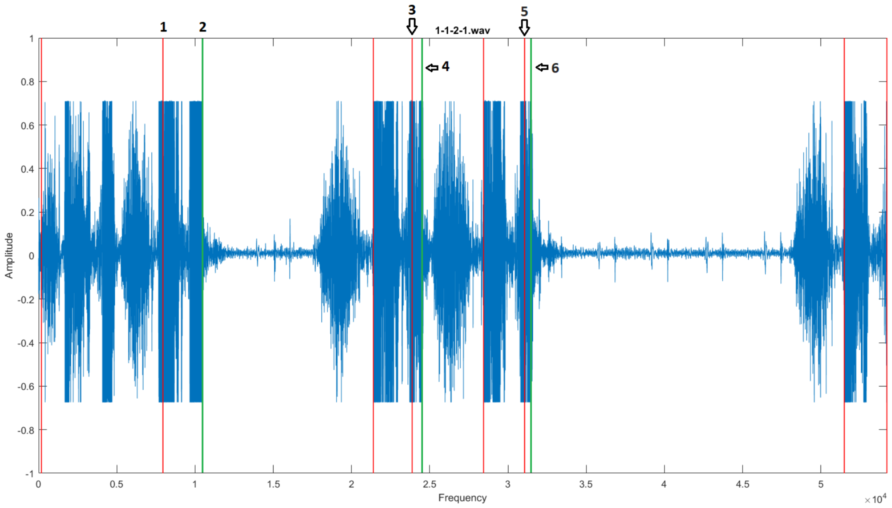

FIGURE 5.16: Cough events with the respective correction (green lines).

- An event of cough is characterized by an inspiration right after or before coughing (black rectangles represent inspiration and red rectangles represent cough, figure 5.17). The way that the algorithm is trained might not always detect it, meaning that a cough event, returned by the algorithm, could have both inspiration and expiration or just one of the two parts.

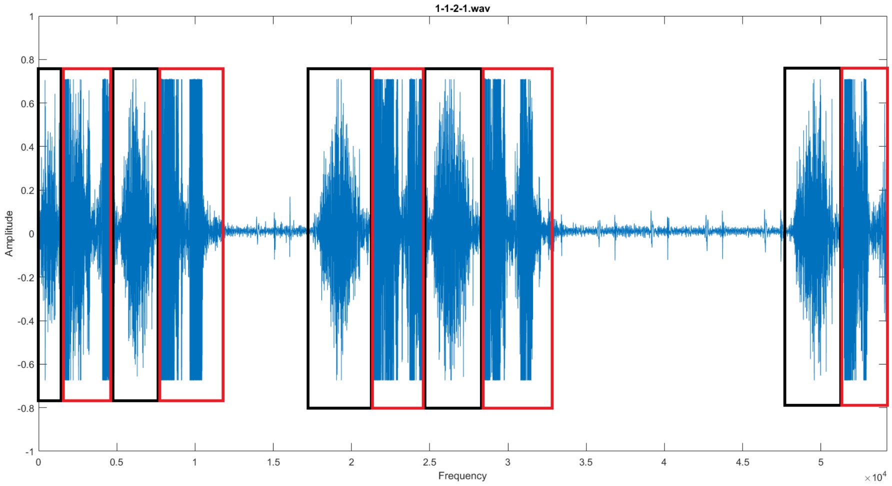

FIGURE 5.17: Cough events with the separation between inspiration (black rectangles) and cough (red rectangles).

- All the sounds were evaluated by taking the samples that correspond to positives, negatives, false positives and false negatives. Only the sounds that have a quality over 90% will be used in the calculations.

After defining how the sounds are going to be evaluated, we are going to analyze the sounds using three different methods: (1) compare the 92 prototype sounds with the 120 Littmann sounds, and show the statistics, (2) remove the Littmann sounds that are not present in the prototype, and show the statistics and (3) compare only the cough sounds that both prototype and Littmann have. Both variables are independent and the data from them does not provide from a standard normal. For that reason, we used the Wilcoxon Rank Sum Test, considering a significance level of

5% and the null hypothesis is: the data in Littmann and prototype are samples from continuous distributions with equal medians. In all the cases, the algorithm was trained with the dataset described in [26] and tested with the dataset created in this thesis. The train set contains an SVM model trained with 28 features from 465 events and it was validated using the Leave-One-Out (Patient) Cross-Validation (LOOCV). Regarding to (1), we obtained the following results.

- Littmann

	Results
Sensitivity/Recall	85.77 ± 29.87%
Specificity	98.85 ± 4.05%
Precision	69.00 ± 46.55%
F1 Score	92.77 ± 17.73%

TABLE 5.1: Results from the cough algorithm, for the Littmann (mean ± standard deviation).

- Prototype

	Results
Sensitivity/Recall	76.97 ± 31.16%
Specificity	99.33 ± 0.03%
Precision	80.63 ± 39.58%
F1 Score	87.62 ± 17.18%

TABLE 5.2: Results from the cough algorithm, for the prototype (mean ± standard deviation).

After running the Wilcoxon test, we determined that the difference between both devices are not significant ($p = 9.1\%$, sensitivity, and $p = 13.1\%$, specificity) and, consequently, we fail to reject the null hypothesis. Considering that F_1 Score is measured by the precision (correct positive results divided by the sum of all positive numbers) and the recall (correct positive results divided by the sum of all real correct positives), the results show a 5% difference for the Littmann, but a lower precision (almost 12% different).

In this case we analyze the sounds that had a quality over 90%, which meant that the Littmann had 120 sounds and the prototype had 92 sounds. To measure the results correctly, we decided to check if without the measurements that the prototype does not have the results would improve. So, for the case (2), we used 90 sounds from each device and we obtained the following results.

- Littmann

	Results
Sensitivity/Recall	83.90 ± 31.97%
Specificity	98.52 ± 0.05%
Precision	65.11 ± 48.08%
F1 Score	92.07 ± 18.91%

TABLE 5.3: Results from the cough algorithm, for the Littmann (mean ± standard deviation), with the sounds equality distributed.

- Prototype

	Results
Sensitivity/Recall	76.97 ± 31.16%
Specificity	99.35 ± 0.03%
Precision	80.63 ± 39.58%
F1 Score	87.62 ± 17.18%

TABLE 5.4: Results from the cough algorithm, for the prototype (mean ± standard deviation), with the sounds equality distributed.

The results improved ($p = 18.6\%$, sensitivity, and $p = 3.7\%$, specificity) indicating that there are significant differences when detecting negative values. The precision of the Littmann was 4% lower than the previous results. There was a small decrease in the metrics, which indicates that, from the 14 sounds removed, most of them were not bad classified and, consequently, the sounds with more false positives and false negatives became more valuable in the calculation, which means a decrease in the sensitivity, specificity and precision (but with a significant difference in the specificity), and, consequently, in the F_1 score. Until now we saw a combination of sounds where some had cough and others were normal or deep respiration; so, using only the cough sounds (32 sounds for each method), case (3), we obtained the following results.

- Littmann

	Results
Sensitivity/Recall	83.90 ± 31.97%
Specificity	99.97 ± 0.00%
Precision	99.84 ± 0.01%
F1 Score	92.07 ± 18.91%

TABLE 5.5: Results from the cough algorithm, for the Littmann (mean ± standard deviation), with the sounds equality distributed and only considering the cough sounds.

- Prototype

	Results
Sensitivity/Recall	76.97 ± 31.16%
Specificity	99.85 ± 0.01%
Precision	99.45 ± 0.03%
F1 Score	87.62 ± 17.18

TABLE 5.6: Results from the cough algorithm, for the prototype (mean ± standard deviation), with the sounds equality distributed and only considering the cough sounds.

Like case (2), in this one the results similar, but having a precision of 99.45% (almost 35% more). After running the Wilkoxon test, we noticed that the difference is not significant ($p = 18.6\%$, sensitivity, and $p = 59.5\%$, specificity). By looking to the tables 5.5 and 5.6, we can conclude that the Littmann can obtain better results when hearing cough, but the difference is not significant. When comparing sounds that are not only cough, it will have an higher rate of false positives. In the same way as the Littmann, the prototype also had higher results, indicating that the normal and deep respirations caused a higher rate of false positives. By looking at the specificity, we can see a small progress between the different tests; on the other hand, the sensitivity stays the same during the three tests, being 7% less than the Littmann (although not significant, as we saw). Comparing our results with [26] we can check that, using all the sounds, we have, using the Littmann, a sensitivity of 85.77% ± 29.87% against 92.3% ± 2.3% of the paper. A difference of almost 8%, which is a huge difference when considering that the sensitivity is one of the most important metrics in the health area. Looking at the prototype, the results are worse, having a sensitivity of 76.97% ± 31.16%. Looking at specificity, both the Littmann (with 98.85% ± 4.05%) and the prototype (with 99.33% ± 0.03%) have surpassed the paper results (84.7% ± 3.3%). Considering only cough sounds, the results did not improve and, actually, decreased in terms of sensitivity. The sensitivity was 83.90% ± 31.97% and 76.97% ± 31.16% on the Littmann and the prototype, respectively, and the specificity was 99.97% ± 0.00% and 99.85% ± 0.01% on the Littmann and the prototype, respectively. We had a higher specificity but lower sensitivity, with a great standard deviation. At the end, we can conclude three different statements:

- The results between the Littmann and the prototype are similar among them, in terms of F_1 score.
- The results from the Littmann and the prototype have a lower sensitivity and higher specificity when compared with the paper.
  - The values of the standard deviation are caused by the amount of false negatives that both Littmann and our prototype found and by only taking into account both positive and false positives that are higher than 0. We used MatLab to calculate the metrics and by using the formulas $nanmean$ (for the mean) and $nanstd$ (for the standard deviation), we are only taking into account values where the cough exists (explaining why the sensitivity is very similar between the three tests).
  - By having only 32 files with cough values, and having plenty of discrepancies in them, it only takes a few very bad results and very good results (i.e. not detecting any cough event when there is and detect all the events that exist in the sound) to raise the standard deviation. This can be possible to see by looking at the precision; when considering only cough sounds, the standard deviation is 0.01% (Littmann) and 0.03% (prototype), but when we consider all the sounds, the standard deviation is 46.55% (Littmann) and 39.58% (prototype).
- There are not significant difference between the Littmann and our prototype.

The requirement NFR07 is fulfilled in both cases, although a higher sensitivity would be desirable, specially when working in critical fields (health, aerospace, among others).

5.6.2 Wheezes

Only one of the twenty subjects had wheezes. This cannot prove anything but it can serve as a proof of concept for future work. After gathering the data, we used the measurements that contained wheezes (both measured in the posterior part of the body, one during the cough test and the other during the deep test). In all cases, the algorithm was trained with the dataset described in [17] and tested with the dataset created in this thesis. Table 5.7 presents the results of the algorithm after running it with the adventitious sound. We used the full 30 features (spectrogram and 29 musical features) that the algorithm provide.

	Number of wheezes in the audio	Number of wheezes detected	Number of wheezes not detected	Number of false positives
Littmann	3	2 (66.6%)	1 (33.3%)	1
Prototype	1	0 (0%)	1 (100%)	2

TABLE 5.7: Results after running the algorithm with the sounds containing wheezes.

Without plenty of data to test the algorithm, it is not possible to take any conclusion of this results. Despite that, if we look at figures 5.18 and 5.19, we can see that the spectrogram of both sounds have different aspects, being the second one the most pixelated. This is one of main problems with the prototype, the sound quality is less so the algorithms based on it will have more difficulty to determine if a specific window of the image represents a adventitious sound.

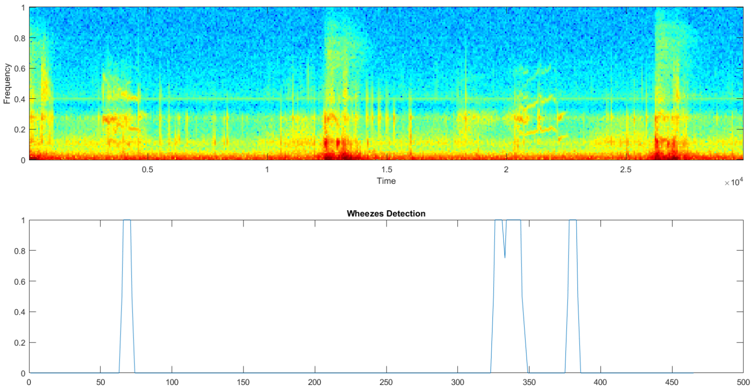

FIGURE 5.18: Littmann sound with 3 wheezes captured: 2 true positives and 1 false positive. The top image is the spectrogram and the bottom image is the result from the algorithm where the values at 1 represent wheeze and at 0 nothing.

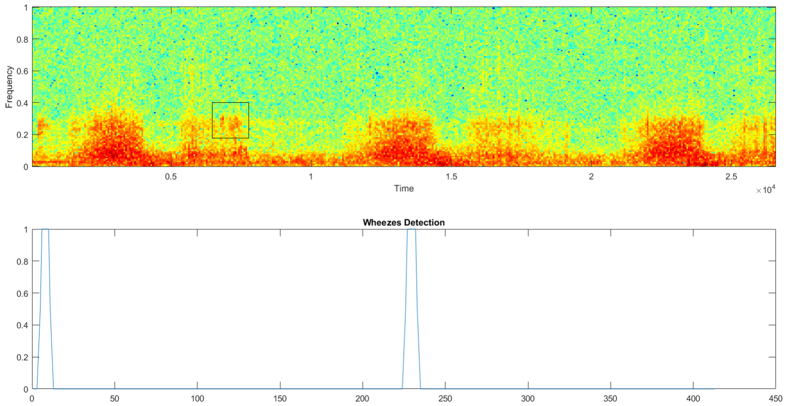

FIGURE 5.19: Prototype sound with 1 wheeze captured: 2 false positive and 1 false negative. In this case, the sound had 1 wheeze event (black square in the top image), but the algorithm failed to detect it. The top image is the spectrogram and the bottom image is the result from the algorithm where the values at 1 represent wheeze and at 0 nothing.

To complement the graphs, the algorithm also returns the space where the wheezes are situated in the spectrogram (figure 5.20 and figure 5.21), showing that there are more points that could be wheezes, but in the final results they are not considered to be wheezes. The red marks represent the wheezes and were added to the final image; the algorithm itself returns the events colored white.

FIGURE 5.20: Georeference of the wheezes in the spectrogram, for the Littmann sound. As it is possible to check, there are more events that where not taken into account when returning the final result (figure 5.18).

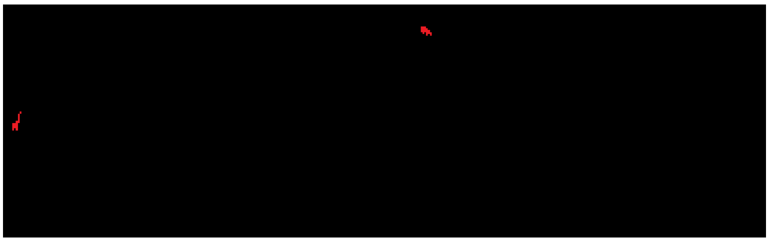

FIGURE 5.21: Georeference of the wheezes in the spectrogram, for the Prototype sound. In this case there are not any other events, but all the events are incorrectly marked as wheezes (although the algorithm marked as wheezes, as it is possible to see on figure 5.19

Unfortunately, we could not test more with these adventitious sounds because, and despite all the efforts made to contact specialists to allow for the tests to run better and with a medical opinion, we did not have any practical help, only theoretical. For this reason, the results cannot reflect the situation and, despite the 66% of the Littmann versus the 0% of the Prototype, we cannot say that the Prototype cannot record wheezes sounds. It is not possible to compare these results with [17].

5.6.3 Comfort

At the end of each test, we asked the volunteers to evaluate the tests considering that 1 is very uncomfortable and 10 being very comfortable. Table 5.8 shows the results from the survey. Test 1 to 6, on both devices, are: 1 to 3, anterior part (normal respiration, cough and deep respiration, respectively) and 4 to 6, posterior part (normal respiration, cough and deep respiration, respectively).

	Prototype						**Littmann**							
	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Mean**	**Std. Dev.**
1	10	10	10	10	10	10	10	10	10	10	10	10	**10,00**	**0,00**
2	9	9	9	6	6	6	9	9	9	6	6	6	**7,50**	**1,57**
3	9	9	9	8	8	9	9	9	9	9	9	9	**8,83**	**0,39**
4	-	-	-	10	10	10	10	10	10	10	10	10	**10,00**	**0,00**
5	9	9	9	9	9	9	10	10	10	10	10	10	**9,50**	**0,52**
6	-	-	-	9	9	9	7	7	7	8	8	8	**8,00**	**0,87**
7	10	10	10	10	10	10	10	10	10	10	10	10	**10,00**	**0,00**
8	9	9	9	9	7	9	9	9	9	9	9	9	**8,83**	**0,58**
9	10	10	10	10	10	10	10	10	10	10	10	10	**10,00**	**0,00**
10	9	9	9	9	9	9	9	9	9	9	9	9	**9,00**	**0,00**
11	-	-	-	8	8	8	9	9	9	9	9	9	**8,67**	**0,50**
12	-	-	-	9	4	6	9	9	9	9	9	9	**8,11**	**1,83**
13	7	7	7	7	7	7	8	8	8	8	8	8	**7,50**	**0,52**
14	8	8	8	8	8	8	8	8	8	8	8	8	**8,00**	**0,00**
15	10	10	10	10	10	10	10	10	10	10	10	10	**10,00**	**0,00**
16	9	9	9	9	9	9	9	9	9	9	9	9	**9,00**	**0,00**
17	10	10	10	9	9	9	9	9	9	9	9	9	**9,25**	**0,45**
18	9	9	9	8	8	8	10	10	10	10	10	10	**9,25**	**0,87**
19	9	9	9	9	9	9	9	9	9	9	9	9	**9,00**	**0,00**
20	10	10	10	10	10	10	9	9	9	9	9	9	**9,50**	**0,52**
Mean	**9,19**	**9,19**	**9,19**	**8,85**	**8,50**	**8,75**	**9,15**	**9,15**	**9,15**	**9,05**	**9,05**	**9,05**		
Std. Dev.	**0,81**	**0,81**	**0,81**	**1,06**	**1,50**	**1,22**	**0,79**	**0,79**	**0,79**	**0,95**	**0,95**	**0,95**		

TABLE 5.8: Results from the comfort evaluation, with the mean and the standard deviation for each test (last two row) and for each volunteer (last two columns).

Tests 2 and 5 represent cough measurements and, looking only to them, we noticed that measuring at the back, with the prototype, has the lowest score. We asked for justifications and more than 50% said that, at the back, the tape was very annoying and the device was very cold. The same arguments cannot be used to justify the values for the Littmann because the stethoscopes head is a very soft and smooth surface.

One aspect that is possible to check is that the standard deviation for the posterior tests are higher than those on the front. This happened because most of the volunteers said that in the back they noticed more both devices and, with the tape and the cold, the prototype achieve a lower score, specially on the cough test.

Summarizing, the comfort was better when using the Littmann because of its rubber and softness head, but the difference is not noticeable, validating NFR02 and NFR03.

5.6.4 Power Consumption

To test this parameter, we connected the prototype to a fully charged power bank with capacity of 2600mAh. Regarding the Littmann, it had a new Duracell AA battery of 2100mAh. The following table shows the number of hours that both devices where on with their respective power source.

	Littmann	**Prototype**
Power Source	Duracell AA Battery	Goodis Power Bank
mAh	2100	2600
Total Hours	15h	14h55min

TABLE 5.9: Number of hours that both the Littmann and the Prototype lasted when running with a fully charged battery.

The 15 hours for the Littmann were calculated based on the real tests. The device was never turned off during 9 hours straight and, in the following day, it went down after 6 hours of tests. During the time, it took 120 valid tests. The 14 hours and 55 minutes of the prototype where calculated based on measuring tests every 2 minutes. The device ran during 13 hours straight and then for 1 hour and 55 minutes. During that time, it took 397 measurements, more than 3 times than the Littmann, in the same time. The difference is huge but the Littmann, as we explained during chapter 2, has plenty of features and a LCD display which can still consume plenty of energy, event in stand-by. On the other hand, the power bank mAh used was not equivalent to the battery mAh, so the results, if the same mAh was used, would be a higher difference in the time between both devices. It does not validate NFR06 because it did not work for 4 days straight.

5.6.5 Cost and Weight

To build the prototype, we had to buy and test some materials and components. After reaching the final state, the total cost was almost 41€.

- Microphone - 5.95$, SparkFun Electret Microphone Breakout[5].
- Genuino 101 - 30.65€, Intel[6]

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[5] https://www.sparkfun.com/products/12758

[6] https://www.element14.com/community/docs/DOC-80459/l/intel-genuino-101-development-board

- Stethoscope Head - 5€, Logiko Echo[7]

The price can be lowered even more because the board used can, actually, be replaced by others that cost 20€ at most, lowering the total cost to 25€. Compared to the Littmann 3200 Electronic Stethoscope, the difference is about 325€, meaning that our prototype costs 14 times less than the Littmann.

Our prototype, on the other hand, does not have any kind of filters, data transmission or batteries associated, but, and predicting with the current components that exist nowadays, we could have raised the cost to no more than 50€, which still is 7x lower when compared to the Littmann. The requirement NFR13 stipulated a maximum cost of 40€ and our final cost was 41€, making it not validated, but if the board used was other (specially because we did not use wireless communications), the price would be lower (i.e. 25€).

Regarding the weight, it can vary very much depending on the build, but considering the functional prototype that we have, the total weight is 100g, being the board 34g and the stethoscope with the microphone 66g. Compared to the Littmann (185g, without the battery), it has almost half of the weight, which is understandable because it has less components inside, but if we consider the batteries, the weights are not going to be very different (assuming the normal 24g for a Duracell AA battery[8]), so the weights of both devices are a plus when considering the wearability and the usage (validating NFR04).

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[7] http://www.ebay.it/itm/FONENDOSCOPIO-STETOSCOPIO-a-testa-piatta-in-ALLUMINIO-DM130-LOGIKO-MORETTI-/222164575996

[8] https://d2ei442zrkqy2u.cloudfront.net/wp-content/uploads/2016/03/Simply _AA_MN1500.pdf

5.7 Remarks

During the chapter we described several aspects related to the tests and problems that we discovered during this phase. We started by going through the different phases of the prototype and how we overpassed the problems found during the pre-tests phase. After that, we detailed the experiments focusing on how the measurements where made, the conditions of the tests and the population size. To get the data from the device to a third party component we though on Bluetooth or Wi-Fi but after some research we discarded both methods; we also tested using an SD Shield but the results were not good so we transfer the data between the device and the third party component (i.e. computer) using an USB cable. With the wireless communications discarded, the wearability was also compromised meaning that the prototype cannot be used without being connected to a computer. After the tests, we analyzed both sound quality and sample rate and the results obtained showed that the prototype is worst with a lower quality sound and an inconstant sample rate.

By looking at cough results, we did not have a significant difference between the Littmann and the prototype, although the sensitivity is slightly higher in the Littmann. Regarding wheezes, we cannot conclude anything because we did not have enough population to do a proper statistical test. In terms of comfort, both have slightly the same values, having the prototype received more critics (i.e. cold diaphragm). Our device did not have a good behavior when being connect to a power bank, but it cost 41€ (almost 8x less than the Littmann) and weights 100g (2x less than the Littmann).

The next chapter will conclude all the work with some reflexions and notes regarding all these results, as well as leaving suggestions that can be useful for future works in this area.

Chapter 6

Conclusions and Future Work

With all the tests and results obtained, we can now close the document by reflecting over the results and explaining what could be different. After that, we are going to leave some suggestions for possible future work.

6.1 Conclusions

We started with the objective to build a prototype that could, efficiently, be comparable to the state of the art electronic stethoscopes and we evaluated our build in four major areas (cough, power consumption, wearability and costs) and also in terms of sound quality, comfort, weight, preprocessing data and detection of wheezes. The attempts to create a cheaper and smaller stethoscope was not 100% successful, but it had major advantages over the state of the art devices.

We made three different tests, for cough detection, that resulted in similar results between all of them, with a few exceptions. First we analyzed all the sounds, and we concluded that both devices had similar results (the differences were not significant), but with a huge standard deviation. Then, we analyze only the sounds that both have; once again, both devices had similar results but the specificity was significantly different, meaning that the removed sounds from the Littmann were correctly identified and, in consequence, the other misclassified sounds had a more impact in the calculations. When we compared only the cough sounds, once again the results were similar, but the standard deviation for the precision had a huge decrease. Because the sensitivity is only calculated based on the sum of positive and false negatives, if this value is not a number (division by 0), it will not enter in the calculations, and that is why the precision suffer a huge decrease. During tests (1) and (2), we had all the sounds, but after removing the non-cough sounds, we had good precision value. Although the precision was the metric with higher discrepancies, the recall (sensitivity) is one of the most important value that we have to consider. Our prototype has a recall of 76% in the three tests which indicates that, with our prototype, 1 in every 4 positive values are not detected (in average, the Littmann has 1 false negative in every 5 positive values - 83.90%). The reason why recall is one of the most important evaluation metrics, specifically in the health area, is because when we miss a positive classification, we can have problems in the future (e.g. in diseases that can lead to death). So, in detriment of the precision, it is rather preferable to have more false positives (lowering precision) that false negatives. When compared the sensitivity of our tests with [26], the results were not good, despite between both Littmann and the prototype the results are similar

Looking at power consumption, wearability and costs, we have also some good results. Regarding wearability, we could not do the data transmission (having used, instead, an USB cable to connect to a computer running the cough algorithm), but we have a small and compact build and, also, the measuring method for our prototype was very different from the Littmann, by using medical tape to hold the prototype in the right place instead of holding by hand (as in the Littmann tests). As we saw, the price for both systems is very different (350€ for the Littmann, 41€ the prototype), meaning that, with the results already discussed, for 8 times less money we can have a good device that can record and detect cough (with the help of a computer) with a reasonable confidence. Finally, one other aspect that was very important was the power consumption. The Littmann took 15 hours (always turned on, 120 tests made) to discharge a full battery and the prototype took 14 hours and 55 minutes (always turned on, 397 tests made) to discharge a full power bank. This was a surprising result because we were expecting to last, at least, 1 full day; we can conclude that if we add something to the build, we will not have a build that can be made to constant monitor a patient (in the future perhaps, but now it is not possible to have that), although it made 397 measurements during the 14 hours and 55 minutes that it lasted.

Regarding the other aspects mentioned (i.e. sound quality, comfort, weight, preprocessing data and wheezes detection), only one aspect our prototype did achieve better results. Starting by the sound quality, we had to use lower silence and saturation parameters so we could have some tests to use with the algorithms. The sound that our prototype records is very low (in normal respiration sounds) and it saturates frequently (in cough sounds), which is bad, specially considering that the main objective was to record pulmonary sound but. The sample rate of the sounds provided by our prototype had a very inconstant frequency (compared to the 4000Hz of the Littmann), which it is not the best scenario because the samples are not taken within the same time and we can have zero or more samples in a simple millisecond.

In terms of comfort, the difference between our build and the Littmann is not significant and, in a scale from 1 to 10, the Littmann got 9.1 ± 0.87 and the prototype got 8.9 ± 1. The difference is in the method used and in the materials of the head of the stethoscopes. In the Littmann, the head is made from a rubber material, being soft and not cold; on the other hand, our prototype is made from aluminum that is always cold and, because the head of the stethoscope was being held by tape, people sometimes complained that, in the back, it was annoying. Regarding the weight, our build was 2 times lighter than the Littmann, which, once again, shows that the wearability is possible. One aspect that also helps in the wearability is the possibility of preprocessing the data and sending it elsewhere. Unfortunately, with our build, we could not even perform simple math inside it and the raw data was sent via USB and shown in a monitor; with the Littmann, the data was sent thorough Bluetooth and they apply some preprocessing methods depending on the sound that they are auscultating, and this is a huge difference from both devices, and that is why the cost is higher on the Littmann.

During the tests, we had 1 subject that had wheezes so we ran the algorithm to see if it could detect them and, for the Littmann, it detected 2 out of 3 and, for our build, it detect 0 out of 1. Unfortunately we did not have more subjects with wheezes, so this test was just to see if it could detect something. Our prototype failed to detect the one wheeze that was captured. This is related to the sound quality because, when we analyze the spectrograms of the sounds, the image of the prototype shows that there was more noise and other constant frequencies present in the sound, and that is why the image is very orange/red.

In conclusion, the results of the tests were not bad, but the aspects related to wearability, quality and preprocessing data makes this build not so successful. By looking at the requirements, the build has not been successful in most of the three types of requirements that we settled, having failed most of the *must have* requirements. But the study opens doors to, in the future, improve this by reducing the price of the built and increasing the quality of the signal.

6.2 Future Work

Developing this work involved a deep study in the embedded systems and health informatics area, to achieve and to know how the processes work, how to use them, what it was behind the algorithms to analyze and detect adventitious sounds.

Regarding the embedded systems, this field is still growing up and every day we see new projects being created or new boards being developed and launched to the market. At the end of the first trimester of the year, RaspberryPi launched a new version of one of the boards that we studied on this project: Raspberry Pi Zero W. It is exactly the same as the studied one, but it adds two extra components: Bluetooth and WiFi. If this board had come earlier in the third trimester of 2016, the project could have changed because, and as we described during the state of the art of the embedded systems, the board does consume plenty of energy and it is very small. With this addition, the board is more interesting and it brings already all the components needed to connect to the Internet or nearby devices. In this field, everyday there is something new that can help to lower the costs, increase reliability, quality, among others.

About the algorithms, every year we have newer and updated versions of algorithms to not only detected but also to predict when a certain problem will occur. Possibly, if new algorithms start to point towards this embedded system's technology, we can see, in the future, technology of this kind being used in critical systems, having a lower battery consumption, high efficiency and lower processing time with good results.

In 2003 a Master's student, in is thesis, developed a project (Wiring) with the goal to create tools for digital projects; at that time, the available microcontroller for this projects costed 100$. Nowadays, that project is called Arduino[46]. To conclude, it is possible to use low cost devices for plenty of jobs (home automation, hobbies, gadgets, among others) and, in the future, it will be possible to apply this technology to replace the expensive tools that exist today also in health informatics applications.

Chapter 7

Planning

This chapter aims at showing how the project evolved during the first and second semesters. The Gantt charts might not be accurate, but represent the work planned and made during both semesters. In the second semester we present two charts: the first represents the plans and the second the real work and the changes made during the semester. The charts were made using the website InstaGantt[1].

7.1 First semester

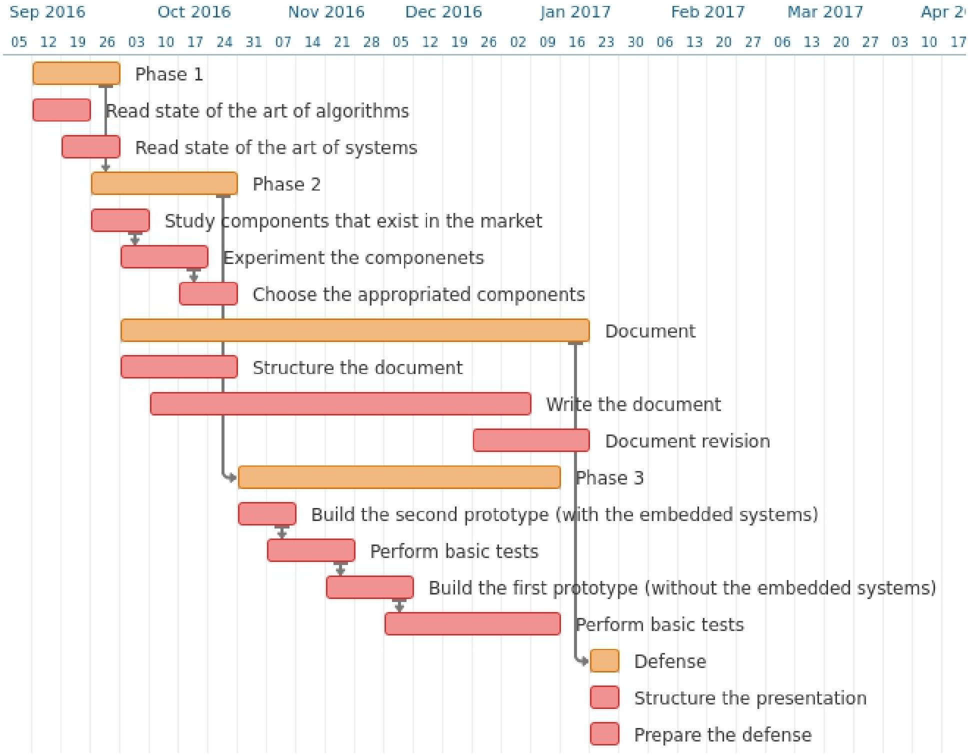

FIGURE 7.1: Gantt chart for the first semester.

In the first semester the work was divided in three phases: study on the state of the art of the algorithms and systems, study and experiment of the components that can fulfill the objectives of the work and the build of the prototype. In the first phase the main objective was to gather information and study what was already built, the costs, algorithms used and pros and cons of systems and algorithms. After that, we started to study and to test some of the components (Arduinos, Raspberrys, microphone, op-amps, among others) to, then, build and test the prototype.

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[1] https://instagantt.com/ - last accessed on 1/June/2017

These tests where simple and it was just to ensure that the prototype worked and, for that reason, most of them were measured using the computer. During the semester, the document was structured and written. After the delivery, the presentation was prepared.

7.2 Second semester

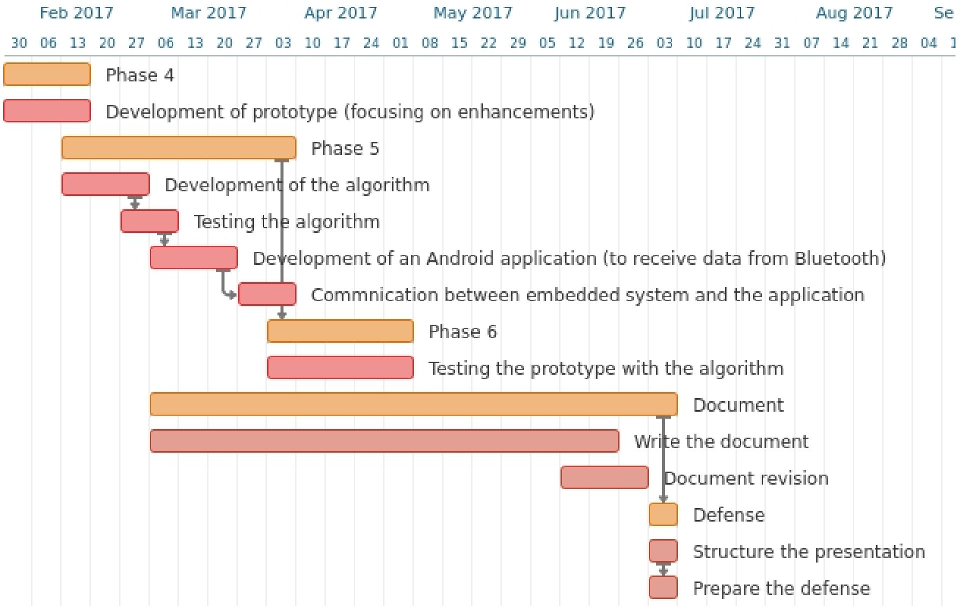

FIGURE 7.2: Planned Gantt chart for the second semester.

For this second semester we also had three different phases planned: finish the development of the prototype, configure the algorithm, test it, develop the Android application to communicate with the system and test final prototype. In the first page the objective was to adjust some aspects of the prototype, set the main board and to test the final build. The second phase was regarding the algorithm and the Android application. Concerning the algorithm, the idea was to configure and test it to obtain better results; the Android application allowed the communication between the prototype and a phone, having the algorithm running inside the phone and showing the results to the user of the prototype. During the semester, the document was being written and, after the final delivery, the presentation was made.

Unfortunately, not everything went according to the plans. Figure 7.2 showed the planned Gantt chart where everything was in a cascade mode and how the phases occurred one after the other; on the other hand, figure 7.3 shows the real Gantt chart where there were no phases and the initial work was completely different and more confusing. During the adjustment of the prototype, it suddenly started to work randomly and the data that we got was random and did not correspond to the real data. With that, we took several weeks to fix and found out that the problem was the board. With that, we also check that it was not possible to send constant data, with high frequency, through Bluetooth, so we did not build an Android application. After replacing the board, we made some tests to check if everything worked properly and the results were that the sound needed to be amplified (chapter 5.1, figure 5.2). As explained in chapter 5.1, the results of the amplification were terrible and we took some time to study other solutions; the final solution can be seen on chapter 5.1, figure 5.3. With the prototype finally done, we started the tests. Only 1 out of 20 subjects had wheezes, so we decided to focus the study more on cough than on wheezes, so, during the tests, we started to review the state of the art, configure the algorithms (both cough and wheezes) and run the tests. After that, we had to reorganize the document to, then, start writing and finishing it. The writing is planned to end almost one month before the deliver specifically because of the revisions that the document will have. After the final delivery, the presentation will be made.

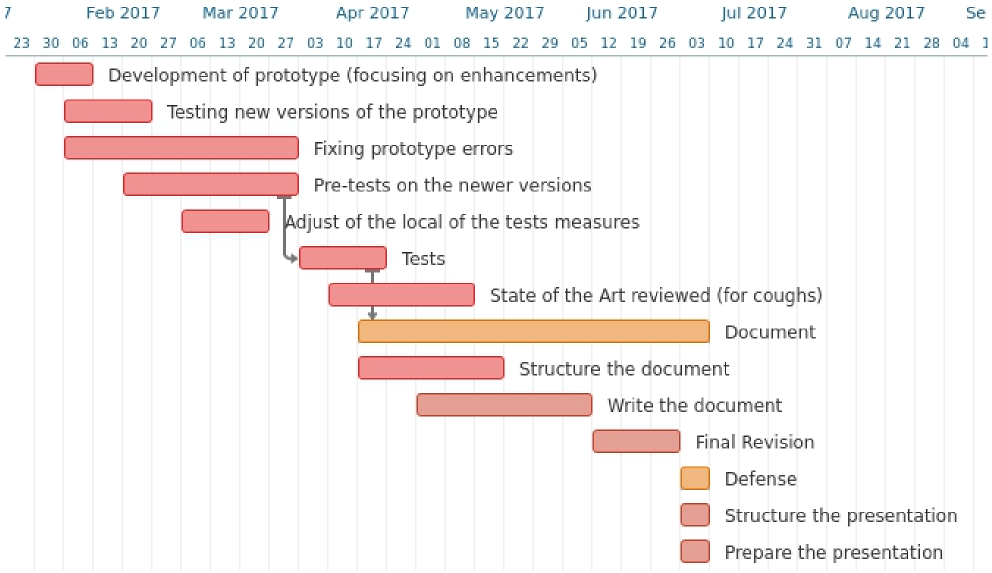

FIGURE 7.3: Real Gantt chart for the second semester.

During both semesters we tried to contact healthcare professionals (specialized in the area that we were studying), but we did not have any replies. We only had a contact with a general practitioner that explained some details regarding the stethoscopes.

Appendices

Appendix A

Requirements

A.1 Wearability

Identifier	NFR01	**Category**	Wearability
Name	Easy to manage/use		
Creation date	02/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Must have*
Description	If the device is going to be used by different patients, we have to make a device that will not cause confusion and stress to make it work. If that happens, the device will not be useful because people will need to take a lot of time to learn it. To solve this issue, the build will be simple, without any complexity around it (no extra buttons or systems around the build). The metric to evaluate is to use a scale (**1 to 10**) and, during the tests, the patients will evaluate it according to the scale.		

TABLE A.1: **NFR01** - Easy to manage/use.

Identifier	NFR02	**Category**	Wearability
Name	Comfortable build to be used by patients		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Must have*
Description	Because the build is going to be used by a person, we have to ensure that all the build is well made to go unnoticed. To this end, **embedded systems** will be used because of their measures (they are **small enough** to be used on pockets or even to be sewn to clothes). The metric to evaluate the comfort is to use a scale (**1 to 10**) and, during the tests, the patients will evaluate it according to the scale.		

TABLE A.2: **NFR02** - Comfortable build to be used by patients.

Identifier	NFR03	**Category**	Wearability
Name	Non-invasive medical build for recording the sounds		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Must have*
Description	When building a prototype, it has to be presented that the build will be used in the patient's body for a long period of time. Because of that, we have to ensure that the build will be smooth (without any roughness) and giving the possibility to move freely. To achieve those results, a vest will be used to **hold the build** and to be more **comfortable** for the patients that are using them. The metric to evaluate the comfort is to use a scale (**1 to 10**) and, during the tests, the patients will evaluate it according to the scale.		

TABLE A.3: **NFR03** - Non-invasive medical build for recording the sounds.

Identifier	NFR04	**Category**	Wearability
Name	Lightweight medical build for recording the sounds		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Should have*
Description	The weight of the build must be low for the patient to use it during long periods of time. For this, the build can be made with light materials (**aluminum**) and the **minimum number of cables will be used**. The weight of the build must no overpass **200g** (2 times the weight of the Littmann 3200 chestpiece).		

TABLE A.4: **NFR04** - Lightweight medical build for recording the sounds.

A.2 Performance

Identifier	NFR05	**Category**	Performance
Name	Wireless communications		
Creation date	11/01/2017	**Author**	João Fernandes
Last modification	22/01/2017		
Version	3	**Prioritization**	*Must have*
Description	Sending data wirelessly is always an advantage because in one hand there are not any wires that can cause mess and, on the other hand, it will increase the scalability of the build (i.e. adding more sensors). Achieving this result implies **researching**, in detail, **different communication protocol** and their **power consumption**. With that, we can then say if a specific protocol is good to be used here or if the wires could do a better work.		

TABLE A.5: **NFR05** - Wireless communications.

Identifier	NFR06	**Category**	Performance
Name	Having a build that has low power consumption		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Must have*
Description	Being a wearable device, the demands for sufficiently long battery autonomy are high. With that, the battery life is a very important aspect that needs to be taken into account. To overcome this, the build will be made using **embedded systems** that have a **low power consumption** (normally they are made with the purpose of consuming less battery and, specially on wearables systems (like Lilypad), that is very important). The metric to evaluate this requirement is the time that it takes to recharge batteries. Being used **4 days straight** is the minimum required.		

TABLE A.6: **NFR06** - Having a build that has low power consumption.

Identifier	NFR07	**Category**	Performance
Name	Classification results comparable to state of the art systems		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	21/01/2017		
Version	2	**Prioritization**	*Must have*
Description	One of the main purpose of studying a new system to collect and process lung sounds are the results that it obtains. If they are not vomparable (a deviation can be accepted because all the systems studied have different results), it means that the system built was not successful. In particular, we will employ the algorithm described in [17] and compare the performance attained with the acquisition using the Littmann stethoscope and using our proposed system. Overpassing this problem is not very easy, but we are going to try to do it by **tweaking** the system (amplify the data, changing features, among others).		

TABLE A.7: **NFR07** - Results similar to state of the art systems.

Identifier	NFR08	**Category**	Performance
Name	Sufficient sampling rate for an ADC		
Creation date	11/01/2017	**Author**	João Fernandes
Last modification	22/01/2017		
Version	2	**Prioritization**	*Must have*
Description	It is not possible to analyze a continuous sound and so, for that, an ADC is need to convert the analog sign to a digital signal. Depending on the levels of resolution, the converted signal can result in a very noise signal or, with an increase in the CPU usage (and consequently consumes more energy), in a very clear sound. To achieve the best sampling rate (in this case the minimum sampling rate) **tests** are **going to be made** where it would be possible to analyze the results and decide **which is the minimum sampling** that can produce a digital sound with the minimum error and CPU usage. Tentatively, 4 kHz sampling rate will be used, as in the Littmann stethoscope and according to the previously described papers on detection of wheezes.		

TABLE A.8: **NFR08** - Sufficient sampling rate for an ADC.

Identifier	NFR09	**Category**	Performance
Name	Sound quality		
Creation date	21/01/2017	**Author**	João Fernandes
Last modification	22/01/2017		
Version	2	**Prioritization**	*Must have*
Description	In a controlled environment, the background noise must be minimal. It is hard to have such conditions, but the less the noise, the better will be the recorded signal. This is also related to the quantization, being necessary to convert the continuous signal to a digital signal. To achieve a better sound quality, the measurements have to be made at **home**, and not in an open area. To complement that, the prototype will be built to lower all the noise and, consequently, **increasing the sound quality** by pointing the microphone directly to the sound source. Having, each embedded systems, different **quantization bits** (10, 12 or more), the conversion (from analog to digital) is dependent on that and the sound can have more or less noise.		

TABLE A.9: **NFR09** - Sound Quality.

Identifier	NFR10	**Category**	Performance
Name	Sound amplification using an op-amp		
Creation date	11/01/2017	**Author**	João Fernandes
Last modification	-		
Version	1	**Prioritization**	*Should have*
Description	The prototype will have a mechanical sound amplification - a stethoscope's head. This component will help amplifying the sounds making unclear (without testing) if there is a need for an extra component to help the amplification of the sound. Despite this, a study can be performed to understand **what exist**s in the market and, then, decide **which one can be used** if there is a need for it.		

TABLE A.10: **NFR10** - Sound amplification using an Op-Amp.

Identifier	NFR11	**Category**	Performance
Name	Pre-processing data in the embedded system		
Creation date	11/01/2017	**Author**	João Fernandes
Last modification	22/01/2017		
Version	2	**Prioritization**	*Should have*
Description	One part is hearing the sounds, the other is to process them to get more readable results. For that, we need to process the sound that is collected and then show the results. But, to save processing, transmission and storage time, it is possible to use the embedded system to pre-process data to, then, be easier to process it elsewhere. Having an embedded system with the capabilities to process data, and because it is a resource that it is not being used at full power, we can use it to **pre-process data** before sending it elsewhere.		

TABLE A.11: **NFR11** - Pre-processing data in the embedded system.

Identifier	NFR12	**Category**	Performance
Name	Processing data in the embedded system		
Creation date	11/01/2017	**Author**	João Fernandes
Last modification	-		
Version	1	**Prioritization**	*Could have*
Description	One part is hearing the sounds, the other is to process them to get more readable results. For that, there is a need of processing the sound that is collected and then show the results. Having an embedded system with capabilities for processing data, and because the hardware is not always 100% in use, taking advantage of it is a **possibility**.		

TABLE A.12: **NFR12** - Processing data in the embedded system.

A.3 Costs

Identifier	NFR13	**Category**	Costs
Name	The build cannot be expensive		
Creation date	01/01/2017	**Author**	João Fernandes
Last modification	11/01/2017		
Version	2	**Prioritization**	*Must have*
Description	Nowadays, there are a lot of technology that can record and process lung sounds. The problem is that they are expensive and, in consequence, a regular person cannot buy one to have it and use it often. By using **embedded systems** (they are the "brain" of the build), we are **lowering the price**. Embedded systems are made to be cheap, but containing a lot of funcionalities. The rest of the build is constructed by using **electronic components** (compatible with the system; they are also **very cheap**) that can connect to the system and record/process the sounds (like the state of the art technology). The metric to evaluate this requirement is to have a build that does not cost more than **40€**.		

TABLE A.13: **NFR13** - The build cannot be expensive.

Appendix B

Declaration

Declaração

Declaration

No âmbito da Dissertação intitulada "*Sistemas Embebidos de Baixo Custo para Aquisição e Análise de Sons Pulmonares*", no Departamento de Engenharia Informática da Universidade de Coimbra, orientada pelos Professores Rui Pedro Paiva e Tiago Cruz e realizada pelo aluno João Tiago Fernandes, autorizo que o mesmo possa efetuar recolha de sons pulmonares e cardíacos (nos pulmões – na parte frontal e na parte traseira –, e na traqueia, respiração normal e funda, tossir), processá-los e usar os dados para serem publicados no documento final da Dissertação. Também autorizo que sejam recolhidas informações pessoais (de acordo com o pedido no protocolo) Todas as informações pessoais, à exceção dos sons recolhidos, serão sempre anonimizadas e serão apenas usados para fins estatísticos.

Within the scope of the Dissertation entitled "*Sistemas Embebidos de Baixo Custo para Aquisição e Análise de Sons Pulmonares*", in the Department of Informatics Engineering of the University of Coimbra, advised by Professors Rui Pedro Paiva and Tiago Cruz and conducted by the student João Tiago Fernandes, I authorize that he can collect pulmonary and cardiac sounds (in the lungs – front and back –, and in the trachea, normal and deep breathing, coughing), process them and publish the results in the final document of the Dissertation. I also authorize the collection of personal information (according to the protocol) All personal information, except the collected sounds, will always be anonymized and will only be used for statistical purposes.

Coimbra, 2017/___/___

____

(assinatura/signature)

Appendix C

Protocol

Patient Identification (PID)

______

1. Personal Information

Date: 2017/___/___

Hour: ___h___

Place: ______________________________________

Sex: M F **Age**: __________ **BMI**: __________

Smoker type (average)[1]: 1 2 3 4 5 6

Physical Exercise (average)[2]: 1 2 3 4 5 6

Respiratory Diseases	

Comorbidities	**Diabetes**	**Anxiety**	**Depression**	**Cardiovascular Diseases**	**Cancer**	**Obesity**

Track Identification (TID)	Description	Position Code	Recorded (mode[3])		Duration
			1	**2**	
1	**Anterior (normal)**	1			15s
2	**Anterior (cough)**	1			15s
3	**Anterior (deep)**	1			15s
4	**Posterior (normal)**	2			15s
5	**Posterior (cough)**	2			15s
6	**Posterior (deep)**	2			15s

---

[1] **1** - does not smoke and never smoked; **2** - does not smoke but it was a smoker in past; **3** - smokes often (1-6 cigarettes per week); **4** - smokes regularly (min 1 cigarettes per day); **5** - smokes very much (min 10 cigarettes per day); **6** - smokes heavily much (more than 1 packet per day).

[2] **1** - does not practice and never practiced; **2** - does not practice but it practiced in past; **3** – practices often (1-2 days per week); **4** - practices regularly (3-4 days per week); **5** - practices very much (5-6 days per week); **6** - practices very much (7 days per week).

[3] **1** – Prototype; **2** – Littmann 3200.

The declaration of the patient must be attached to this document

2. Position Codes

Figure 1 Respiratory System (anterior view)

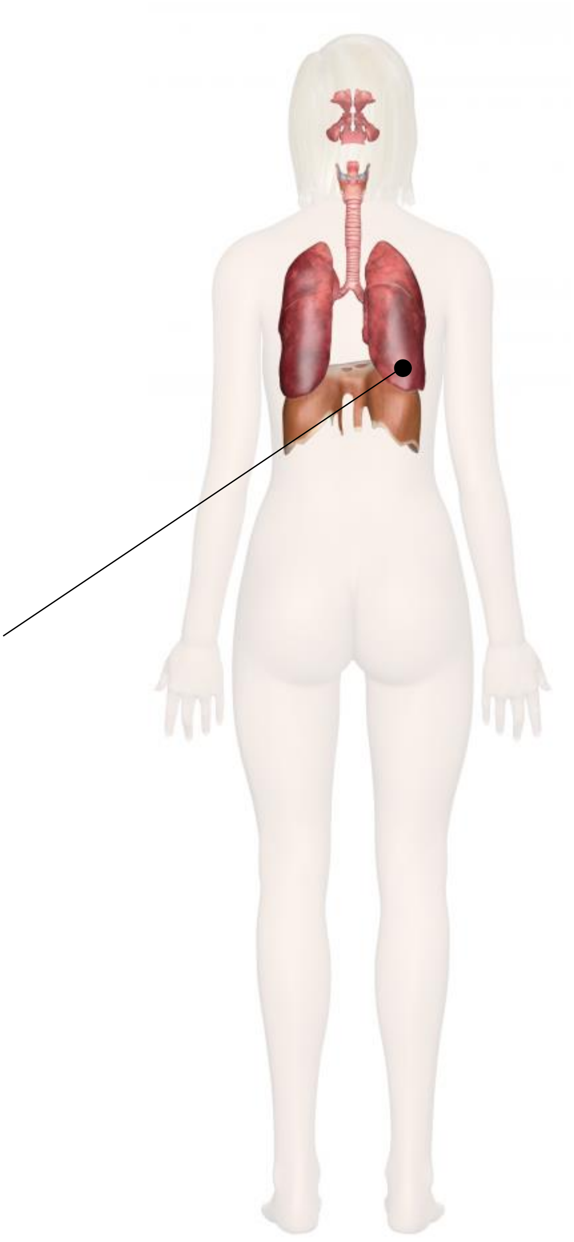

Figure 2 Respiratory System (posterior view)

Images from **http://www.innerbody.com/anatomy/respiratory**

The declaration of the patient must be attached to this document

3. Protocol

1. Inform the patient about the procedures and obtain the consent (by signing the declaration).
2. Put the patient in the correct position.
3. With the correct mode, perform the measurements without any movements, and save the results with the following format: <PID>_<POSITION>_<TID>_<MODE>.txt
4. Perform tasks 3 for all the TID.
5. Perform tasks 3-4 for all the modes.
6. Send the records to the Laptop and group them in the same folder.
7. The:
    a. .txt files are converted to .wav files with the help of MatLab.
    b. Littmann's .wav files that result from step 4 are used to:
        i. compare with the values recorded by the prototype;
        ii. validate the prototype.
8. All files are stored in a folder named <PID>.

Appendix D

Littmann Results

	Littmann Results				Total of Samples
	Positives	Negatives	False Positives	False Negatives	
../1/1_1_1_2.wav	0	60000	0	0	60000
../1/1_1_2_2.wav	18872	41128	0	0	60000
../1/1_1_3_2.wav	0	60000	0	0	60000
../1/1_2_4_2.wav	0	60000	0	0	60000
../1/1_2_5_2.wav	14782	45218	0	0	60000
../1/1_2_6_2.wav	0	49432	10568	0	60000
../2/2_1_1_2.wav	0	57872	2128	0	60000
../2/2_1_2_2.wav	12428	47572	0	0	60000
../2/2_1_3_2.wav	0	59112	888	0	60000
../2/2_2_4_2.wav	0	60000	0	0	60000
../2/2_2_5_2.wav	8302	51698	0	0	60000
../2/2_2_6_2.wav	0	60000	0	0	60000
../3/3_1_1_2.wav	0	60000	0	0	60000
../3/3_1_2_2.wav	6510	53490	0	0	60000
../3/3_1_3_2.wav	0	60000	0	0	60000
../3/3_2_4_2.wav	0	60000	0	0	60000
../3/3_2_5_2.wav	4144	44651	0	11205	60000
../3/3_2_6_2.wav	0	60000	0	0	60000
../4/4_1_1_2.wav	0	60000	0	0	60000
../4/4_1_2_2.wav	5580	54420	0	0	60000
../4/4_1_3_2.wav	0	60000	0	0	60000
../4/4_2_4_2.wav	0	60000	0	0	60000
../4/4_2_5_2.wav	8960	50873	167	0	60000
../4/4_2_6_2.wav	0	60000	0	0	60000
../5/5_1_1_2.wav	0	60000	0	0	60000
../5/5_1_2_2.wav	11734	47914	352	0	60000
../5/5_1_3_2.wav	0	59232	768	0	60000
../5/5_2_4_2.wav	0	60000	0	0	60000
../5/5_2_5_2.wav	7736	48148	0	4116	60000
../5/5_2_6_2.wav	0	58152	1848	0	60000
../6/6_1_1_2.wav	0	60000	0	0	60000
../6/6_1_2_2.wav	7948	52052	0	0	60000
../6/6_1_3_2.wav	0	60000	0	0	60000
../6/6_2_4_2.wav	0	60000	0	0	60000
../6/6_2_5_2.wav	5582	54418	0	0	60000
../6/6_2_6_2.wav	0	60000	0	0	60000
../7/7_1_1_2.wav	0	60000	0	0	60000
../7/7_1_2_2.wav	0	51242	0	8758	60000
../7/7_1_3_2.wav	0	60000	0	0	60000
../7/7_2_4_2.wav	0	60000	0	0	60000
../7/7_2_5_2.wav	9744	50256	0	0	60000
../7/7_2_6_2.wav	0	57536	2464	0	60000
../8/8_1_1_2.wav	0	57168	2832	0	60000
../8/8_1_2_2.wav	8200	51800	0	0	60000
../8/8_1_3_2.wav	0	60000	0	0	60000
../8/8_2_4_2.wav	0	57920	2080	0	60000
../8/8_2_5_2.wav	2928	46362	0	10710	60000
../8/8_2_6_2.wav	0	60000	0	0	60000
../9/9_1_1_2.wav	0	60000	0	0	60000
../9/9_1_2_2.wav	1664	58336	0	0	60000
../9/9_1_3_2.wav	0	60000	0	0	60000

../9/9_2_4_2.wav	0	60000	0	0	60000
../9/9_2_5_2.wav	0	51817	0	8183	60000
../9/9_2_6_2.wav	0	60000	0	0	60000
../10/10_1_1_2.wav	0	55504	4496	0	60000
../10/10_1_2_2.wav	6800	53200	0		60000
../10/10_1_3_2.wav	0	46280	13720	0	60000
../10/10_2_4_2.wav	0	60000	0	0	60000
../10/10_2_5_2.wav	12153	47847	0	0	60000
../10/10_2_6_2.wav	0	60000	0	0	60000
../11/11_1_1_2.wav	0	60000	0	0	60000
../11/11_1_2_2.wav	12572	47428	0	0	60000
../11/11_1_3_2.wav	0	60000	0	0	60000
../11/11_2_4_2.wav	0	60000	0	0	60000
../11/11_2_5_2.wav	9734	45744	0	4522	60000
../11/11_2_6_2.wav	0	60000	0	0	60000
../12/12_1_1_2.wav	0	60000	0	0	60000
../12/12_1_2_2.wav	13296	46704	0	0	60000
../12/12_1_3_2.wav	0	60000	0	0	60000
../12/12_2_4_2.wav	0	60000	0	0	60000
../12/12_2_5_2.wav	6594	51699	0	1707	60000
../12/12_2_6_2.wav	0	60000	0	0	60000
../13/13_1_1_2.wav	0	60000	0	0	60000
../13/13_1_2_2.wav	7992	52008	0	0	60000
../13/13_1_3_2.wav	0	59160	840	0	60000
../13/13_2_4_2.wav	0	60000	0	0	60000
../13/13_2_5_2.wav	13880	46120	0	0	60000
../13/13_2_6_2.wav	0	60000	0	0	60000
../14/14_1_1_2.wav	0	60000	0	0	60000
../14/14_1_2_2.wav	7958	52042	0	0	60000
../14/14_1_3_2.wav	0	57488	2512	0	60000
../14/14_2_4_2.wav	0	60000	0	0	60000
../14/14_2_5_2.wav	9592	50408	0	0	60000
../14/14_2_6_2.wav	0	60000	0	0	60000
../15/15_1_1_2.wav	0	45618	14382	0	60000
../15/15_1_2_2.wav	16128	43872	0	0	60000
../15/15_1_3_2.wav	0	56422	3578	0	60000
../15/15_2_4_2.wav	0	60000	0	0	60000
../15/15_2_5_2.wav	3858	51617	0	4525	60000
../15/15_2_6_2.wav	0	60000	0	0	60000
../16/16_1_1_2.wav	0	48000	12000	0	60000
../16/16_1_2_2.wav	11905	48095	0	0	60000
../16/16_1_3_2.wav	0	60000	0	0	60000
../16/16_2_4_2.wav	0	58808	1192	0	60000
../16/16_2_5_2.wav	21821	38179	0	0	60000
../16/16_2_6_2.wav	0	53792	6208	0	60000
../17/17_1_1_2.wav	0	60000	0	0	60000
../17/17_1_2_2.wav	12720	47280	0	0	60000
../17/17_1_3_2.wav	0	60000	0	0	60000
../17/17_2_4_2.wav	0	60000	0	0	60000
../17/17_2_5_2.wav	11584	48416	0	0	60000
../17/17_2_6_2.wav	0	60000	0	0	60000
../18/18_1_1_2.wav	0	60000	0	0	60000
../18/18_1_2_2.wav	7440	52560	0	0	60000
../18/18_1_3_2.wav	0	60000	0	0	60000

../18/18_2_4_2.wav	0	60000	0	0	60000
../18/18_2_5_2.wav	18251	41749	0	0	60000
../18/18_2_6_2.wav	0	60000	0	0	60000
../19/19_1_1_2.wav	0	60000	0	0	60000
../19/19_1_2_2.wav	8434	51566	0	0	60000
../19/19_1_3_2.wav	0	60000	0	0	60000
../19/19_2_4_2.wav	0	60000	0	0	60000
../19/19_2_5_2.wav	3236	56764	0	0	60000
../19/19_2_6_2.wav	0	60000	0	0	60000
../20/20_1_1_2.wav	0	60000	0	0	60000
../20/20_1_2_2.wav	11426	48574	0	0	60000
../20/20_1_3_2.wav	0	60000	0	0	60000
../20/20_2_4_2.wav	0	60000	0	0	60000
../20/20_2_5_2.wav	5739	35583	0	18678	60000
../20/20_2_6_2.wav	0	60000	0	0	60000

Appendix E

Prototype Results

	Prototype Results				Total of Samples
	Positives	Negatives	False Positives	False Negatives	
../1/1_1_1_1.wav	0	53273	0	0	53273
../1/1_1_2_1.wav	33189	21051	0	0	54240
../1/1_1_3_1.wav	0	53273	0	0	53273
../1/1_2_4_1.wav	0	53273	0	0	53273
../1/1_2_6_1.wav	0	53273	0	0	53273
../2/2_1_1_1.wav	0	53273	0	0	53273
../2/2_1_2_1.wav	8820	39626	0	4973	53419
../2/2_1_3_1.wav	0	53273	0	0	53273
../2/2_2_4_1.wav	0	53273	0	0	53273
../2/2_2_5_1.wav	5330	45241	0	2769	53340
../2/2_2_6_1.wav	0	53273	0	0	53273
../3/3_1_1_1.wav	0	53273	0	0	53273
../3/3_1_2_1.wav	15618	38129	0	0	53747
../3/3_1_3_1.wav	0	53273	0	0	53273
../3/3_2_4_1.wav	0	53273	0	0	53273
../3/3_2_5_1.wav	11132	24409	0	17732	53273
../3/3_2_6_1.wav	0	53273	0	0	53273
../4/4_2_4_1.wav	0	53273	0	0	53273
../4/4_2_5_1.wav	0	44035	0	9240	53275
../4/4_2_6_1.wav	0	53273	0	0	53273
../5/5_1_1_1.wav	0	53273	0	0	53273
../5/5_1_2_1.wav	9404	37232	0	6891	53527
../5/5_1_3_1.wav	0	53273	0	0	53273
../5/5_2_4_1.wav	0	53273	0	0	53273
../5/5_2_5_1.wav	12356	41133	0	0	53489
../5/5_2_6_1.wav	0	53273	0	0	53273
../6/6_2_4_1.wav	0	53273	0	0	53273
../6/6_2_6_1.wav	0	53273	0	0	53273
../7/7_1_1_1.wav	0	53273	0	0	53273
../7/7_1_2_1.wav	8660	44749	0	0	53409
../7/7_1_3_1.wav	0	53273	0	0	53273
../7/7_2_4_1.wav	0	53273	0	0	53273
../7/7_2_5_1.wav	0	40342	0	12931	53273
../7/7_2_6_1.wav	0	53273	0	0	53273
../8/8_1_1_1.wav	0	53273	0	0	53273
../8/8_1_2_1.wav	6023	37984	0	10135	54142
../8/8_1_3_1.wav	0	51227	2046	0	53273
../8/8_2_4_1.wav	0	53273	0	0	53273
../8/8_2_5_1.wav	2902	44070	0	6489	53461
../8/8_2_6_1.wav	0	53273	0	0	53273
../9/9_1_1_1.wav	0	53273	0	0	53273
../9/9_1_2_1.wav	2406	51144	0	0	53550
../9/9_1_3_1.wav	0	53273	0	0	53273
../9/9_2_4_1.wav	0	53273	0	0	53273
../9/9_2_5_1.wav	9490	43924	0	0	53414
../9/9_2_6_1.wav	0	53273	0	0	53273
../10/10_1_1_1.wav	0	46892	6381	0	53273

../10/10_1_2_1.wav	13933	32905	0	8110	54948
../10/10_1_3_1.wav	0	53273	0	0	53273
../10/10_2_4_1.wav	0	53273	0	0	53273
../10/10_2_5_1.wav	10803	29921	0	12721	53445
../10/10_2_6_1.wav	0	53273	0	0	53273
../11/11_2_4_1.wav	0	53273	0	0	53273
../11/11_2_5_1.wav	11528	39733	0	2063	53324
../11/11_2_6_1.wav	0	53273	0	0	53273
../12/12_2_4_1.wav	0	53273	0	0	53273
../12/12_2_5_1.wav	15906	37514	0	0	53420
../12/12_2_6_1.wav	0	53273	0	0	53273
../13/13_1_1_1.wav	0	53273	0	0	53273
../13/13_1_2_1.wav	27610	28241	0	0	55851
../13/13_1_3_1.wav	0	53273	0	0	53273
../13/13_2_4_1.wav	0	53273	0	0	53273
../13/13_2_5_1.wav	10935	42700	0	0	53635
../13/13_2_6_1.wav	0	53273	0	0	53273
../14/14_1_1_1.wav	0	53273	0	0	53273
../14/14_1_2_1.wav	7673	45701	0	0	53374
../14/14_1_3_1.wav	0	53273	0	0	53273
../14/14_2_4_1.wav	0	53273	0	0	53273
../14/14_2_5_1.wav	7228	35303	0	10763	53294
../14/14_2_6_1.wav	0	53273	0	0	53273
../15/15_1_1_1.wav	0	44446	8827	0	53273
../15/15_1_2_1.wav	9171	44648	0	0	53819
../15/15_1_3_1.wav	0	53273	0	0	53273
../15/15_2_4_1.wav	0	53273	0	0	53273
../15/15_2_5_1.wav	0	38614	0	14660	53274
../15/15_2_6_1.wav	0	53273	0	0	53273
../16/16_1_1_1.wav	0	53273	0	0	53273
../16/16_1_2_1.wav	21233	32969	0	0	54202
../16/16_1_3_1.wav	0	53273	0	0	53273
../16/16_2_4_1.wav	0	53273	0	0	53273
../16/16_2_5_1.wav	18563	34830	0	0	53393
../16/16_2_6_1.wav	0	53273	0	0	53273
../17/17_1_1_1.wav	0	53273	0	0	53273
../17/17_1_2_1.wav	18428	35665	0	0	54093
../17/17_1_3_1.wav	0	53273	0	0	53273
../17/17_2_4_1.wav	0	53273	0	0	53273
../17/17_2_5_1.wav	21159	18010	0	14106	53275
../17/17_2_6_1.wav	0	53273	0	0	53273
../18/18_1_1_1.wav	0	53273	0	0	53273
../18/18_1_2_1.wav	10401	43730	0	0	54131
../18/18_1_3_1.wav	0	53273	0	0	53273
../18/18_2_4_1.wav	0	53273	0	0	53273
../18/18_2_5_1.wav	12365	36815	0	4192	53372
../18/18_2_6_1.wav	0	52008	1265	0	53273
../19/19_1_1_1.wav	0	53273	0	0	53273
../19/19_1_2_1.wav	5098	48445	0	0	53543
../19/19_1_3_1.wav	0	53273	0	0	53273

../19/19_2_4_1.wav	0	53273	0	0
../19/19_2_5_1.wav	4564	48760	0	0
../19/19_2_6_1.wav	0	53273	0	0
../20/20_1_1_1.wav	0	44038	9235	0
../20/20_1_2_1.wav	10680	40957	2132	0
../20/20_1_3_1.wav	0	52413	860	0
../20/20_2_4_1.wav	0	52470	803	0
../20/20_2_5_1.wav	16503	36778	0	0
../20/20_2_6_1.wav	0	53273	0	0

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