



Jeremie De Seabra

Licenciado em Ciências da Engenharia Electrotécnica e
de Computadores

Wearable Monitoring System for Assistance Dogs

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Orientador: Yves Rybarczyk, PhD, Faculdade de
Ciências e Tecnologia da Universidade Nova de Lisboa
Co-orientador: Arnaldo Batista, PhD, Faculdade de
Ciências e Tecnologia da Universidade Nova de Lisboa

Júri:

Presidente: Prof. Doutor José António Barata de Oliveira
Arguente: Prof. Doutor Raúl Eduardo Capelo Tello Rato
Vogal: Prof. Yves Philippe Rybarczyk

Wearable Monitoring System for Assistance Dogs

Dispositivo *vestível* de monitorização de Cães de Assistência

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Abstract

Despite the recent progresses in robotics, autonomous robots still have too many limitations to reliably help people with disabilities. On the other hand, animals, and especially dogs, have already demonstrated great skills in assisting people in many daily situations. However, dogs also have their own set of limitations. For example, they need to rest periodically, to be healthy (physically and psychologically), and it is difficult to control them remotely. This project aims to “augment” the Assistance dog, by developing a system that compensates some of the dog weaknesses through a robotic device mounted on the dog harness. This specific study, involved in the COCHISE project, focuses on the development of a system for the monitoring of dogs activity and physiological parameters.

Key-Words:

Assistance-Dog, Wearable devices, Remote monitoring, Assistive technologies, Wireless, Signal processing, Respiratory Rate, Heart Rate, Behavior.

Sumário

Apesar dos recentes avanços na área da robótica, os robôs autônomos ainda apresentam demasiadas limitações para poderem assistir com segurança pessoas portadores de deficiência. Por outro lado, vários animais, de entre os quais com especial destaque o cão, já demonstraram grande capacidade em assistir pessoas em diversas tarefas do dia-a-dia. No entanto, os cães também têm as suas limitações. Por exemplo, precisam de descansar periodicamente, precisam de estar de boa saúde (física e psicológica), e é complicado controlá-los remotamente. Este projeto visa “aumentar” o cão de assistência, ao desenvolver um sistema que compensa algumas das fragilidades do cão através de um dispositivo robótico montado no arnês do cão. Este estudo em particular, enquadrado no projeto COCHISE, foca-se no desenvolvimento de um sistema de monitorização da atividade e de parâmetros fisiológicos de cães.

Palavras-Chave:

Cão de Assistência, Dispositivo *vestível*, Monitorização remota, Tecnologias de assistência, Sem-Fios, Processamento de sinal, Ritmo Respiratório, Ritmo Cardíaco, Comportamento.

TABLE OF CONTENTS

1.	Introduction	1
1.1.	Motivation.....	2
1.2.	Goals	2
1.3.	Dissertation Structure	2
2.	State Of The Art	3
2.1.	Assistance Dog	3
2.2.	Augmented Dog.....	3
2.3.	Dogs Health	4
2.4.	Measurements Invasiveness.....	4
2.5.	Measurement and Observation	4
2.6.	Data Acquisition and Processing	5
2.7.	Sensor Types and Characteristics	6
2.8.	Communication.....	7
2.9.	Signal Analysis	8
2.9.1.	Wavelets	8
2.9.2.	Common-mode rejection	9
3.	Proposal	11
4.	Development.....	13
4.1.	Selecting Components	13
4.2.	First Version	14
4.2.1.	Hardware	14
4.2.2.	Software.....	16
4.2.3.	Tests & Results.....	18
4.3.	Second Version	20
4.3.1.	Hardware	21

4.3.2. Software.....	24
4.3.3. Tests & Results.....	25
4.4. Third Version (Final).....	28
4.4.1. Hardware	28
4.4.2. Software.....	32
5. Experimental Results.....	39
5.1. Activity Detection.....	39
5.2. Respiratory Rate and Heart Rate	40
5.3. Other Results.....	41
6. Conclusions & Future Work.....	43
7. Publications & Presentations	45
8. References	47
Appendix	A1

FIGURE INDEX

Figure 1 - Schematic of signal transmission and reception between the dog and the owner.	1
Figure 2 - Difference Amplifier [C. Kitchin and L. Counts, A Designer’s Guide to Instrumentation Amplifiers, 3rd Edition. Analog Devices, Inc, 2006, pp. 1–5]	9
Figure 3 - Schematic of the connection between the Arduino Board and the JY-MCU Bluetooth module. The dotted wire represents a pull-up resistor that is only connected when the Bluetooth module needs to be programmed.	14
Figure 4 - Schematic of the connection between the Sensors and Bluetooth Module with the Arduino Board.	15
Figure 5 – First application developed to assist during the sensors testing, with main features identified: 1 – connection options, 2 – Channel selection, 3 – Signal window, 4 – FFT window, 5 – Data Analysis window.	17
Figure 6. Diagram of the experiment. The laboratorial equipment is represented in Blue, while the Prototype elements are represented in Orange. The visualization tool is represented in Green. The Green and Orange arrow represents the wireless Bluetooth connection between the devices. The black arrows represent electrical connections between components, while the black rectangle represents a physical connection between the Shaker and the Sensor.....	18
Figure 7. Permanent Magnet Shaker. Sensor fixated to the Shaker moving axis (Right picture).....	18
Figure 8. Signal Generator (Left) and Universal Counter (Right).	19
Figure 9. Example (@4,48Hz) of data acquired during the experiment. Original Signal (top), FFT (bottom), peak Frequency detected (encircled in red).	19
Figure 10 - Shield Schematic.....	21
Figure 11 - Arduino with developed shield to connect the sensors and the Bluetooth module, and 6xAA batteries to power the ensemble.	22
Figure 12 - Schematic of the protective Box made for the board. The base (left) and the cover (right).	22
Figure 13. The board inside the protective Box. Closed Box (large picture) and opened Box (small picture).	23

Figure 14 - Box, sensors and battery pack attached to the reflective coat using Velcro Strips.....	23
Figure 15 – Second application developed to assist during the sensors testing, with main features identified: 1 – connection options, 2 – Channel selection, 3 – Signal window, 4 – FFT window, 5 – Data Analysis window.	24
Figure 16 - Shiva with the device installed on her back.....	25
Figure 17 - Accelerometer axis orientation, as they were placed on the dogs.	25
Figure 18 - Y Axis read by the accelerometers. Blue: Walking, Red: Running. [Signal length: 14s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)	26
Figure 19 - Y Axis read by the accelerometer (Median). A: Standing, A-B: Seating, B-C: Seating more vertically, C-D: Standing. [Signal length: 1m 20s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)	27
Figure 20 - Respiratory Rate. Blue: Z2-Z1 axis. Red: Median of the signal. [Signal length: 20s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)	27
Figure 21 - Schematic of the developed board.	29
Figure 22 - Final board.	30
Figure 23 - Sensor/RJ45 adaptor schematic (left) and board (right).	30
Figure 24 - Finished boards. Main board with Bluetooth module on the left, and adaptor with sensor on the right.	31
Figure 25 - Schematic of the protective Box made for the last version of the board. Base (left) and cover (right).	31
Figure 26 - Final system placed on the dog harness.....	32
Figure 27 - GUI showing the data captured by the accelerometers in real time. In the top left signal, the option to display the FFT was activated.	33
Figure 28 - Representation of the Activity identification rules.	34
Figure 29 – Visualization of cmr.....	35
Figure 30 – Virtual dog representation. From drawing to 3D model.	36
Figure 31 – Rigged model ready for animation.....	36
Figure 32 - Live information Window.	37
Figure 33 - Example of the statistics made available to the user.	38
Figure 34 - System placed on Shiva, a female Pit-bull.	39
Figure 35 – Wavelet analysis of a portion of the signal logged during an experiment with the dogs.....	40

TABLE INDEX

Table 1. Short comparative between the relative range, power consumption, bandwidth and price of Bluetooth, ZigBee, Wi-Fi, GSM/GPRS, IrDA, MICS devices.	7
Table 2 - Tested Frequency (TF) Vs. Measured Frequency (MF). TF is the inputted frequency in the motor, and MF is the Frequency at which a spike is detected in the FFT performed by the PC.....	20
Table 3 - Activity transition Detection time.	39
Table 4 - Component cost distribution.	41

1. INTRODUCTION

This thesis is inserted in a broader European project called *Cochise* that has as main objectives to be able to facilitate the “dialog” between persons with disabilities and their Assistance dogs. This can be achieved by monitoring various dog parameters such as the dog barking, the posture (through a microphone, accelerometer, gyroscope, pressure sensors, or others), the environment (through a GPS sensor, a camera or a IR barrier for example), providing this information to the owner or some other responsible person in a useful way, and offering the possibility to send commands back to the dog (using any device such as a computer, a cell phone, a tablet or some kind of specialized peripheral), as represented in Figure 1.

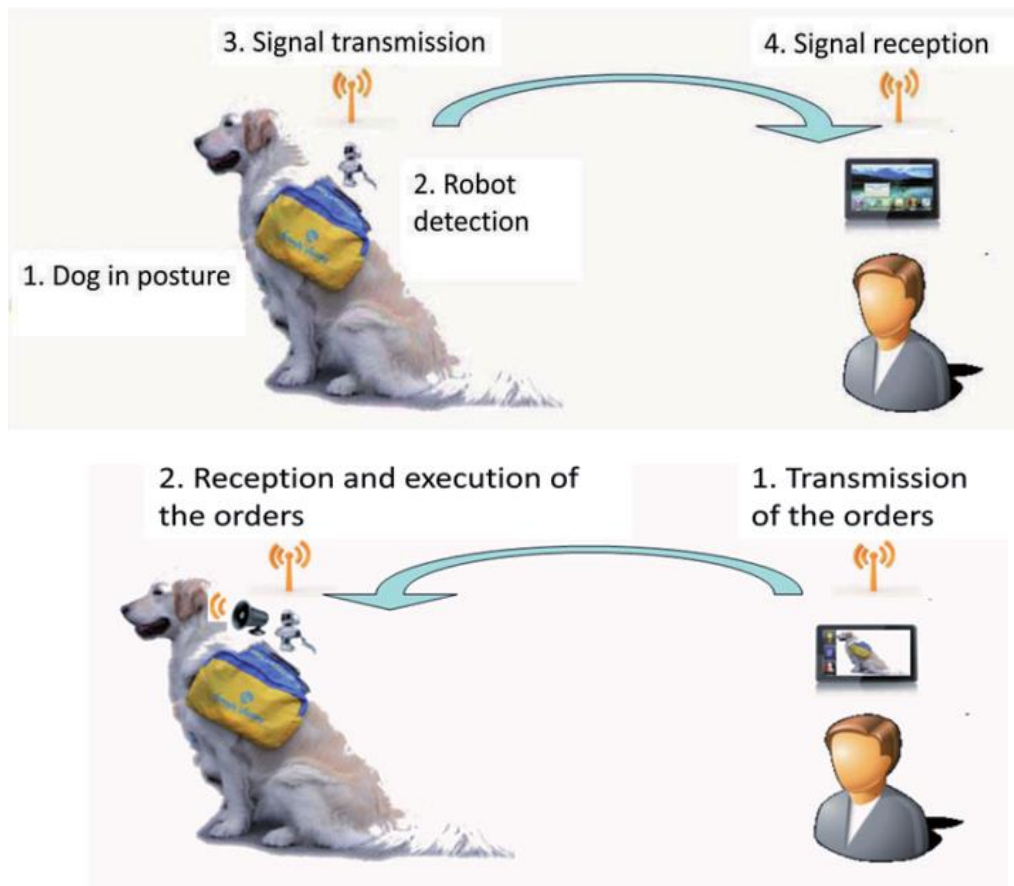


Figure 1 - Schematic of signal transmission and reception between the dog and the owner.

This thesis will focus essentially in acquiring information about the dog, and in transmitting that information in a clear and user friendly way.

1.1. **Motivation**

Inclusion and accessibility are concepts that are increasingly important in our society, as well as the notions of animal well-being and respect. This dissertation offers not only a way to work on both of those subjects, but also an opportunity to study, understand, and maybe improve the millennial and very successful companionship and relationship between dogs and humans.

1.2. **Goals**

The main goal of this thesis is to develop a device to study and analyse the behaviour, health, and general well-being of dogs in real-time and continuously in order to potentiate the Human/Dog relationship. With this goal in mind, the gathered information should also be made available in a user friendly manner on a normal Personal Computer (PC) and/or mobile device.

1.3. **Dissertation Structure**

The Second Chapter of this thesis will define the concepts of Assistance Dog, Augmented Dog, Dogs Health, and Invasiveness as well as review the current state of existing dog monitoring devices and the technology that is typically used for this kind of devices, and for the one that it is aimed to be developed in this project.

In the Third Chapter the project proposal is presented by defining the kind of device that will be developed as well as more specific goals that ought to be achieved.

The Forth Chapter describes the development stages of this project, with all prototype versions, and intermediate results with respective conclusions.

The Fifth Chapter contains the experimental results achieved with the last version of the device that was developed, followed by the conclusions and future work are provided in the Sixth chapter.

2. STATE OF THE ART

2.1. Assistance Dog

In the European Union, in 2002, 16.4% of the population in working-age (16-64 years old) reported that they had a long standing health problem or disability [1]. One of the existing ways to improve the mobility, autonomy, self-esteem and safety of this significant portion of the population is through the use of assistance dogs.

The term *Assistance Dog* corresponds to the national (Portugal) and international harmonized terminology to designate the various categories of assistance dogs for people with disabilities, including guide dogs, hearing dogs and service dogs [2]. In 2008, solely in the European Union, over 13,000 people already benefited from this type of aid [3]. To be able to have the assistance dog status, the animal must be educated and trained in an establishment that meets quality and ethics standards, and that uses specially qualified trainers [2], thus seeking to maximize the safety of every person involved, and also to ensure the well-being of the animal.

2.2. Augmented Dog

Despite major advances in robotics, particularly in emulation and simulation of mechanical behavior and intelligence of various types of animals, such robots still have too many limitations in order to be able to assist people with disabilities. By contrast, animals, among which the dog, have already demonstrated to be able to reliably assist people in many everyday tasks. However, similarly to the robots, the dog also has its own limitations [4], being one of the most important ones the necessity of guaranteeing the dog's well-being - both physical and psychological.

In order to take advantage of the strengths and minimize the weaknesses of each (the dog and the robot) the concept of *Augmented Dog* arises. The aim is to “augment” the dog, to facilitate human-dog interaction and vice-versa. This is done by placing, on the dog, a small robot whose task is to mediate the interaction between the dog and the human. This robot analyzes and interprets various behavioral and/or physiological signals from the dog, and transmits them to the human. In turn, the human can react to this data by sending a command to the robot that will trigger a reaction in the animal through a predetermined stimulus for which the dog has been trained to react appropriately [4].

2.3. **Dogs Health**

Dogs can suffer from many kind of health problems, and while it's obvious why physiological and physical problems can directly impact the assistance dog performance of its daily tasks, psychological problems can also lead to indirect consequences. For example dogs can experience stress (both acute and chronic) due to a wide range of situations such as a noisy environment, being restraint, an inappropriate training, transportation, or housing, the presence of strangers, or when faced with completely new or/and unexpected situations. In response, the animal may have a physiological or behavioral reaction, both of them, or even one as a consequence of the other [5][6]. Many behavioral indicators may be considered. For instance, tremors, circular locomotion, posture, sighs, vocalizations, urination, the tail's agitation (its frequency and direction), and the panting [7]. Similarly, various physiological indicators can also be considered, such as changes in the body temperature and heart rate [8], the heart rate variability [9], the ratios between cortisol and creatinine, and also the amounts of catecholamine, epinephrine, and norepinephrine measured in the urine [7][10].

2.4. **Measurements Invasiveness**

In order to study the different symptoms, both physiological and behavioral, numerous methods can be used, some of which are more or less intrusive than the others. There are three main categories that differentiate the degree of invasiveness of the procedure: Non-invasive, invasive, and minimally-invasive. The non-invasive methods are defined as those which do not require piercing the skin, do not require any contact with mucous membranes, and do not require entrance trough body cavities – neither natural nor artificial body cavities. Opposed to these methods are the invasive ones, which are defined as those that require entrance through a body cavity, that disrupt normal bodily functions, or as those which result in body perforation. Minimally-invasive methods are invasive methods that attempt to perform the same procedure using techniques that allow them to be accomplished through the smallest possible incision [11][12].

2.5. **Measurement and Observation**

As mentioned in section 2.3, stress in dogs may manifest itself through various behavioral or physiological symptoms. Several methods are commonly used in order to monitor each one. For instance, in order to study behavioral stress related symptoms, one

of the most common technique employed is through the usage of video recordings [13][14] or photographs [15], or by observing directly the subject of the study. The observation may or may not be made in real time, and may be made by one or more persons [16][17], and it may also be made by strangers (in the dogs perspective) – the persons conducting the study, professional veterinary personnel, or simply volunteers – or directly by the owners through the completion of questionnaires [8][18]. In order to study physiological symptoms, slightly more invasive techniques are typically used, such as blood sample collection, the usage of electrodes that require to shave and clean areas of the dog to perform ECG [9] and EMG [19] analysis, or to obtain blood pressure data [5]. Other common ways are through urine sample collection, which usually require the presence of a person in order to acquire a mid-stream sample [10], or by measuring the body temperature – typically measured through rectal temperature – which requires a momentary restraint of the dog [8].

2.6. **Data Acquisition and Processing**

In order to acquire signals from the real world into the devices that will process, analyze and interpret them, specialized data acquisition systems (DAQ) or Microcontrollers can be used. A DAQ device acts as a bridge between a computer and the signals that are to be analyzed. In order to accomplish that, three main features are used: The signal conditioning circuitry, the analog-to-digital converter (ADC), and the computer bus. The signal conditioning component task is to manipulate the signal so that it has an adequate form to input into an ADC, by using amplification, attenuation, filtering and isolation circuitry. The task of the ADC is to sample periodically an analog signal in such a way that it can be reconstructed after being transferred over the computer bus that manages the communication between the DAQ device and the computer to which it is connected. Typically they are connected through an USB, PCI, PCI Express or Ethernet port, but can also be connected wirelessly through Wi-Fi [20].

For more dedicated functions, embedded systems can be preferable. Embedded Systems are microprocessor or microcontroller based systems that are designed to a very specific task and to be not reprogrammable by the end user [21][22]. While microprocessors usually have a much higher processing power than microcontrollers, the fact that they need to be assembled with external RAM, ROM, buffer, I/O ports, and more, makes them

more costly to design and develop. Since microcontrollers already have almost everything built-in, this leads to more compact and less costly products, making them a very good choice for applications where very high processing power is not required [23].

2.7. **Sensor Types and Characteristics**

Choosing the correct sensor for the desired application is absolutely vital, as it can be the difference between achieving the established goals or not.

Several types of sensors can be used as part of wearable health-monitoring systems, and each type of sensing technology produces different kind of data about different bio signals. One of the most commons (for humans) is the usage of Skin electrodes that measure the electrical activity of the heart showing the contraction and relaxation phases of the cardiac cycle, producing an Electrocardiogram (ECG). Similarly the Heart rate and the Oxygen saturation can both be measured through a pulse oximeter, allowing to measure the frequency of the cardiac cycle and the oxygenation level present in the blood. Another very important measurement is the body's ability to generate heat as well as the ability to get rid of it. Generally the measurement of the body temperature is made using temperature probes or skin patches. The Respiration rate is also many times measured as a way of determining the number of respiration cycles (inspiration and expiration) in a given time unit, generally using piezoelectric/piezoresistive sensors. To measure the brain activity electrodes can be placed on the scalp in order to obtain an electroencephalogram (EEG). To measure the electrical signals produced by the muscular activity skin electrodes can be used, producing an electromyogram (EMG). The heart sounds can also be obtained using a phonocardiograph. The heart sound (and indirectly heart rate) is obtained by placing on the chest a microphone (stethoscope). The body movement can also be measured by placing accelerometers in key points to measure the acceleration forces produced by those movements [24].

An exhaustive list of sensor types is almost impossible to produce, as almost anything can be used to measure directly or indirectly many variables that can be indicative of the subjects health. For each situation, context, and respective requirements (subject, mobility, autonomy, comfort, accuracy, etc.) a sensor can be more or less adequate, and several options may be available.

2.8. Communication

Several technologies and different protocols are available to send data wirelessly from a microcontroller to a mobile device such as through Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4), Wi-Fi (IEEE 802.11), GSM/GPRS, Infrared (IrDA) or the Medical Implant Communication Service (MICS), each of which has some advantages and disadvantages over the others depending on the application [24], as it is summarized in the table below (Table 1).

Table 1. Short comparative between the relative range, power consumption, bandwidth and price of Bluetooth, ZigBee, Wi-Fi, GSM/GPRS, IrDA, MICS devices.

	Range	Power Consumption	Bandwidth	Price
Bluetooth	Medium	Low	Medium	Low
ZigBee	Short	Medium	Low	Low
Wi-Fi	Medium	High	High	High
GSM/GPRS	Long	Medium	Medium	High
IrDA	Short	Low	Medium	Low
MICS	Short	Low	Low	-

An exhaustive list of communication technologies and protocols would be almost impossible to compile as a lot of protocols exist for almost every application, some of which are proprietary. For each application one or more technologies may be more or less suitable.

2.9. Signal Analysis

For many applications, signal processing is absolutely essential. This is especially true in biomedical applications, where many times the signals that ought to be analyzed are very low energy signals that can be easily lost amongst other signals or even noise.

Some techniques can simply consist of calculating the mean, power, or energy of a signal. Many kind of filters can also be applied in order to extract the information that is desired, but not everything can be filtered, and it's one of the reasons that spectral analysis, such as the Fast Fourier Transform (FFT), is very important to understand what is being analyzed. Other tools can be used in different scenarios, such as Wavelets or the Common-Mode rejection property.

2.9.1. Wavelets

While the FFT can be a very useful and powerful tool in signal analysis, it has its own limitations. If the signal is non-stationary (i.e. the signal has time varying frequencies), it may not be possible to determine if a signal component exists at a given time. For non-stationary signals, the Short Fourier Transform (STFT), can be used. This method performs FFT analysis on short windows of time where the signal is considered stationary, producing a time-frequency result where it is possible to observe the changes in frequency at a given time. [25] However the STFT also has a limitation. It has a uniform resolution all along the time-frequency plane, meaning that some information may be lost in both low and high frequency sides of the spectrum.

The Wavelet Transform (WT), similarly to the STFT, offers a decomposition of the data in a time-frequency representation, with the difference that the WT adapts the window size to the frequency, meaning that the time-frequency plane is non-uniformly partitioned and more suitable for many real-world signals [26]. Various functions that control how the resolution will change on the plane exist, and for that reason different wavelets can be applied to a signal in order to obtain different results.

2.9.2. Common-mode rejection

Common-Mode rejection (CMR) is a very prevalent feature in electronics, and particularly in biomedical electronics since it is at the core of instrumentation and difference amplifiers (Figure 2).

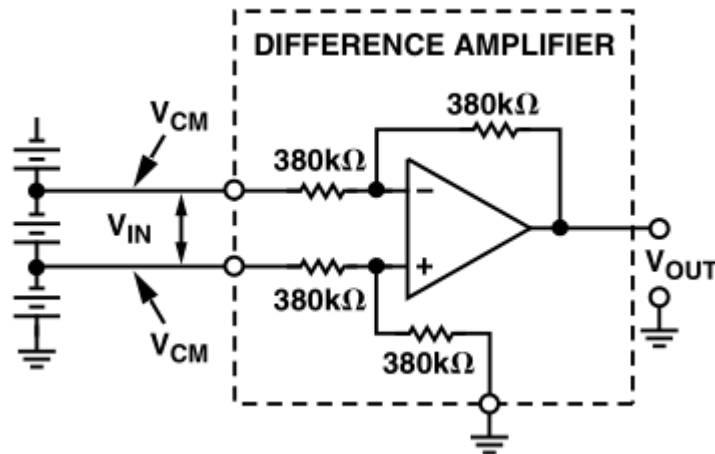


Figure 2 - Difference Amplifier [C. Kitchin and L. Counts, A Designer's Guide to Instrumentation Amplifiers, 3rd Edition. Analog Devices, Inc, 2006, pp. 1-5]

“An instrumentation amplifier is a device that amplifies the difference between two input signal voltages while rejecting any signals that are common to both inputs” [27]. While Instrumentation amplifiers offer superior isolation comparatively to difference amplifiers they both perform the same operation. The property of canceling out any signal that are common while amplifying differential signals is called Common-Mode rejection (CMR). Many different implementations of the Common-Mode rejection can be made, both electronically or in software.

3. PROPOSAL

During this thesis work, a device will be developed that shall allow the acquisition of various kind of signals in order to be able to monitor remotely a wide range of parameters from the dog. Since this thesis will focus on the acquisition and the transmission of information, the system that will be developed does not need yet to take into account the other systems that will be developed in other works of project Cochise group, which will allow, remotely, the reception of instructions for the dog.

By developing this device, a clear objective is traced of reproducing the best from the majority of existing monitoring/observation devices and techniques, and trying to answer directly to their weak points and flaws.

To solve the insufficiencies from existing monitoring systems, several requirements must be met. It must be low-cost, so that it is easily available to a large segment of the population. So that we can monitor the dog permanently, it must be light and small, wireless, and non-invasive. The device should also be able to produce scientifically accurate data in real-time about the dog's activity, behavior, and some physiological parameters. Remote monitoring tools should also be made available, so that professionals can scrutinize more acutely the dog's health at any time, from anywhere. Since the potential public for this kind of devices can be of different age groups and can be of different backgrounds a clear and friendly user interface (UI) will have to be included in this project. Summarizing, the device should have the following characteristics:

- Low Cost
- Light/Small
- Wireless
- Non-Invasive
- Accurate and Unbiased
- Real time analysis capabilities
- Activity, physiological and Behavioural Monitoring
- Friendly/Clear UI;

Ultimately, the objective is to produce a tool that is not only useful for granting the dog's well-being and for providing information to the owner, but also a tool that is useful for dog trainers, healthcare professionals, ethologists and other scientists.

4. DEVELOPMENT

4.1. Selecting Components

To begin with, it was important to select the three main components that the device needed to have: Data acquisition, Sensors and Wireless communications.

Firstly, the sensors had to be chosen since depending on the type of data and communication protocols from the sensors, different data acquisition devices could be more or less suitable. After considering several options, it was decided to use two MPU6050 accelerometer/gyroscope. The fact that accelerometers do not need to be in direct contact with the dog skin was the main motivation for using this type of sensors, because it means that it is possible to perform measurements without shaving the dog, and consequently it implies that it is easier to place it correctly and for longer periods of time. Other characteristics were also considered for this decision, such as the small form factor of this kind of sensors, the robustness, and the lightness. Choosing, more specifically, the MPU6050 happened since it offers good performance and sensibility at a low cost. The fact that it encompasses also a gyroscope meant that more useful data could be extracted.

Having selected the sensor, it was now possible to choose a data acquisition device. The choice fell on the popular Arduino Uno. It offers enough processing power, good communication option, and it is cheap. Overall it is a good prototyping tool, easy to program with extended documentation available and with a very comprehensive set of free open source libraries.

To communicate wirelessly, the chosen option was to use a Bluetooth module, since it offers a good range/power-consumption ratio. They are also cheaply available, and with the price in mind as a differentiating factor the preferred Bluetooth module was a JY-MCU.

Having selected all three main components it was now possible to start building the device, always keeping in mind the system requirements previously defined in the project proposal.

4.2. First Version

Not only it was necessary to setup the devices, but also the real capabilities and sensibility of the sensors were unknown and needed to be explored. To accomplish this, some hardware and software had to be put together.

4.2.1. Hardware

Main Components:

- (1) Breadboard;
- (1) Arduino UNO;
- (1) JY-MCU Bluetooth Module;
- (2) MPU6050.

Initially an Arduino board was connected to the computer through a Serial connection. The microcontroller (MC) was programmed to send a simple text message to the computer. Once the text was successfully received the Bluetooth module was added on a breadboard and connected to the Arduino.

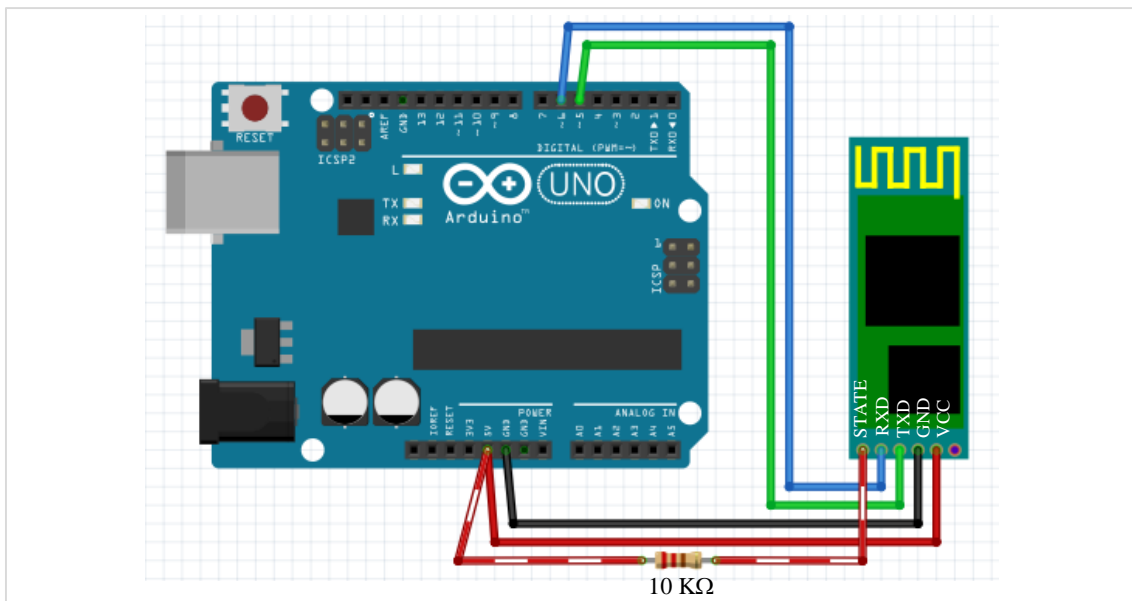


Figure 3 - Schematic of the connection between the Arduino Board and the JY-MCU Bluetooth module. The dotted wire represents a pull-up resistor that is only connected when the Bluetooth module needs to be programmed.

The MC was then programmed to send the same text message to the computer, but now using the Bluetooth module instead. On the computer, the terminal emulator PuTTY was configured to receive the Bluetooth data with the following parameters:

- Speed (baud): 9600
- Data bits: 8
- Stop Bits: 1
- Parity: None
- Flow Control: None

After having successfully received the text message, connecting the pull-up resistor (as shown in Figure 3), the command AT+BAUD8 was sent to the Bluetooth device to change its baud rate to 115200. Changing the previous configuration of PuTTY to include the new baud rate, the message was again successfully received, confirming that the baud rate had indeed changed. Having the communication set and running, the system was now ready to start reading data from the sensors.

Both MPU6050 accelerometer/gyroscope sensors were simultaneously connected to the Arduino Board, using initially a small breadboard to simplify the connections between the sensors and the board. Both sensors share almost every wire with the exception of the AD0 pin, as represented in Figure 4. This difference in the AD0 connection defines if the sensor will be set to use the default I²C address (0x68) or the alternative one (0x69) when set as high, as defined in the MPU6050 Arduino library. In this case it is desired that both sensors run simultaneously, therefore they must have different addresses.

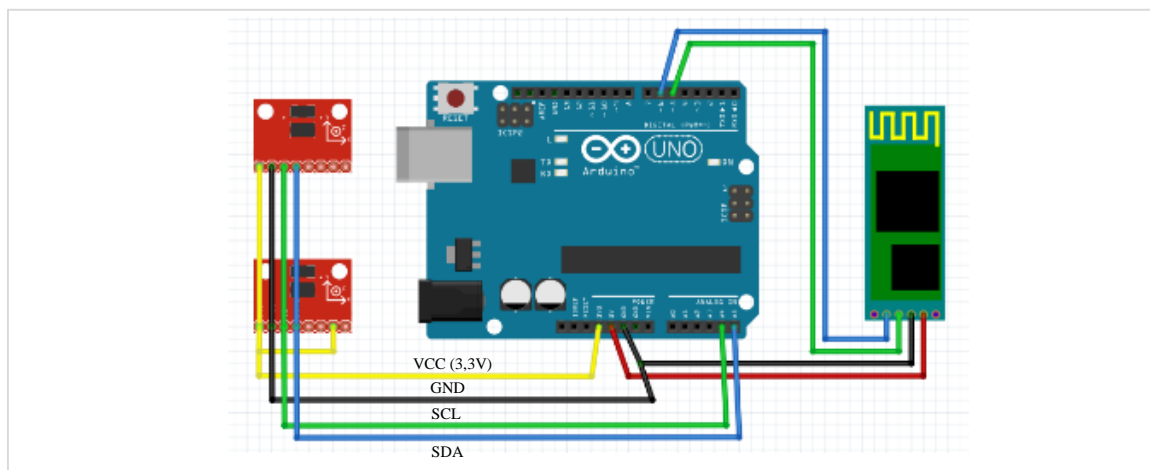


Figure 4 - Schematic of the connection between the Sensors and Bluetooth Module with the Arduino Board.

After setting up the connections as described above, the MC was programmed to read the data from the 3 accelerometer axis and the 3 gyroscope axis of both sensors, and to send those twelve variables via Bluetooth. Re-using the configurations previously used,

the data was successfully read again in the computer. With everything connected and communicating correctly an exact sample rate had to be defined in order to be able to read the data without suffering any aliasing errors due to incorrect down sampling operations.

From all the signals that are going to be analyzed, the one that has the widest range of frequencies is the respiratory rate. The respiratory rate of a dog can fluctuate between 0.16 Hz and 4 Hz (for an average resting dog the breathing rate is approximately 0.4 Hz) [28], and knowing that the maximum frequency value that the FFT comprises is $f_{sampling}/2$, the minimum sample rate would need to be 12 Hz. To play on the safe side, and to be able to observe other phenomena, it was decided that the sample rate should be 25 Hz.

Initially the Arduino function *millis* was used to measure the time elapsed, and to read and send the sensors data each $1/f_{sampling}$ seconds, but after some initial tests it was quickly established that this method lacked the precision required.

The program was then re-written to use the MC timer interrupts instead of *millis*. In order to avoid possible aliasing problems, the sample rate of the sensors was lowered changing the RA_SMPLRT_DIV register to 0x27 ($0x27 = 39d$, and $10000/(39+1) = 25$ Hz). The main loop of the program reads the data as fast as it can, and when the Interrupts fires the program sends the data over Bluetooth. On the Arduino side, using the function *millis* to print the elapsed time between Interrupts, it was verified that the precision was very high. Nevertheless the time between the incoming data on the computer was the real important variable, and in order to make these measurements some software had to be written.

4.2.2. Software

In order to measure the elapsed time between messages, a program was written in C# to record a text file containing the system time on each message received. Analyzing that data in Excel it was possible to verify that the data arrived with very precise intervals of time. Several frequencies were tested changing the Interrupt Timer value, and the results kept following the expected values. After this first validation, some additional tests had to be done, which required a more elaborate program to be written.

In this new program a graphical user interface (GUI) was developed to enable a real time analysis of the data read, and to allow a intuitive correlation with the actions performed on the sensors. When the user launches the program he must establish the connection with the device. For that a Bluetooth icon is placed on the lower left corner of

the window (identified as feature 1, in Figure 5 below), where after being clicked it expands a small menu prompting to choose between the devices that the program find connected to the computer. In the same area, a small recording button is placed to enable or disable the file recording option. After having successfully established the connection between the PC and the device, the user should select which axis signal from which accelerometer should be displayed (feature 2, in Figure 5). After selecting one or more options the signal is displayed in real time in the Signal window (feature 3, in Figure 5), and simultaneously the FFT Window (feature 4, in Figure 5) displays also in real time the FFT performed over a 125 samples window (5 seconds @25Hz). Separately in the Data Analysis window (feature 5, in Figure 5) for the same 125 samples window, the extracted signal mean value, power, energy, and two main signal frequencies are displayed.

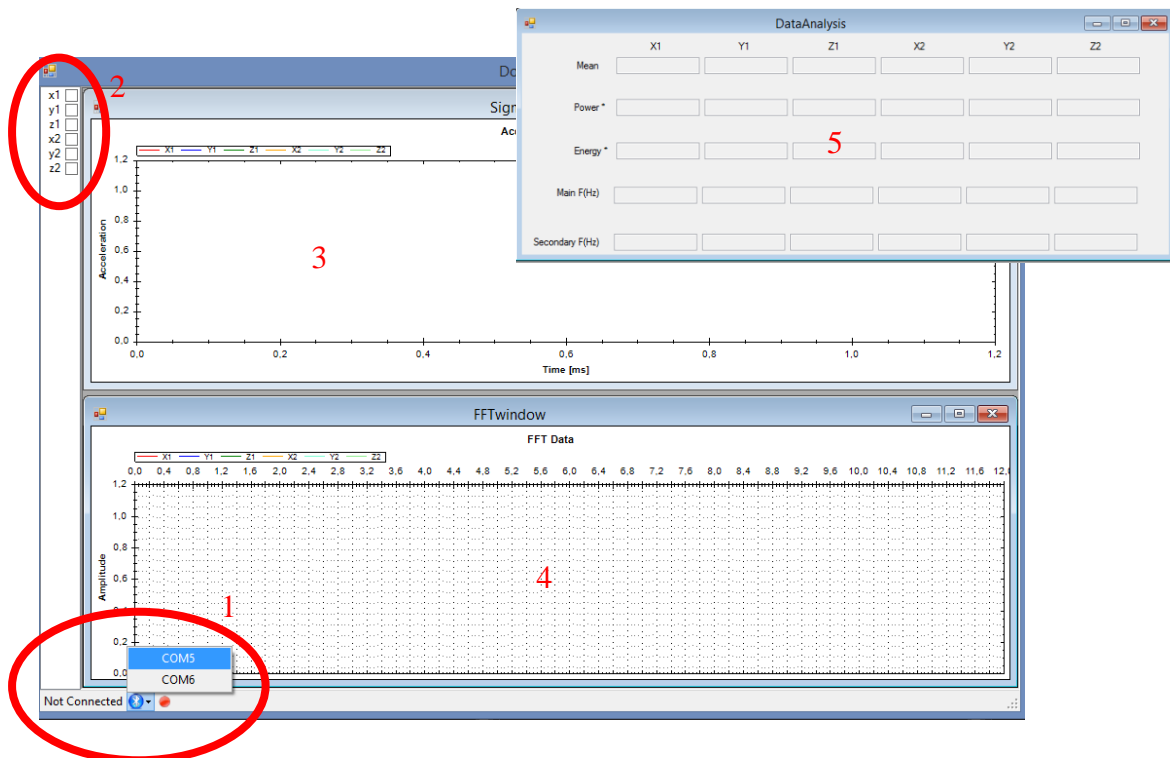


Figure 5 – First application developed to assist during the sensors testing, with main features identified: 1 – connection options, 2 – Channel selection, 3 – Signal window, 4 – FFT window, 5 – Data Analysis window.

Multitasking capabilities had to be implemented, using Background Workers in order to preserve the flow of incoming data without losing the ability to display the data in real time.

After having completed this tool everything was ready to test the system has a whole.

4.2.3. Tests & Results

Having passed successfully the intermediate tests that were performed along the build, a final one was devised. This last test consisted on placing one of the sensors on a Permanent Magnet Shaker (PMS) (Figure 7) set to shake at a predetermined frequency and measuring the frequency of the received signal using a Fast Fourier Transform (FFT), as shown below, in Figure 6.

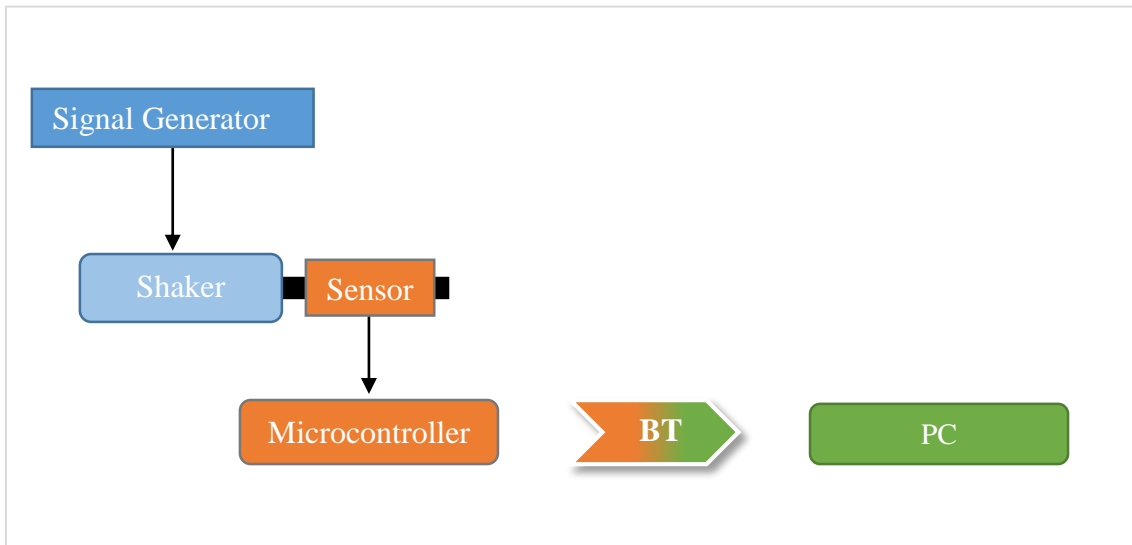


Figure 6 - Diagram of the experiment. The laboratorial equipment is represented in Blue, while the Prototype elements are represented in Orange. The visualization tool is represented in Green. The Green and Orange arrow represents the wireless Bluetooth connection between the devices. The black arrows represent electrical connections between components, while the black rectangle represents a physical connection between the Shaker and the Sensor.

Before starting the experiment, one of the sensors was attached to the PMS (LDS V406)



Figure 7 - Permanent Magnet Shaker. Sensor fixated to the Shaker moving axis (Right picture).

The Permanent Magnet Shaker (PMS) oscillation frequency was controlled using a signal generator outputting a sinusoidal wave at a determined frequency. For each frequency tested, the frequency was fine-tuned using a universal counter to visualize its exact value, as depicted in Figure 8.

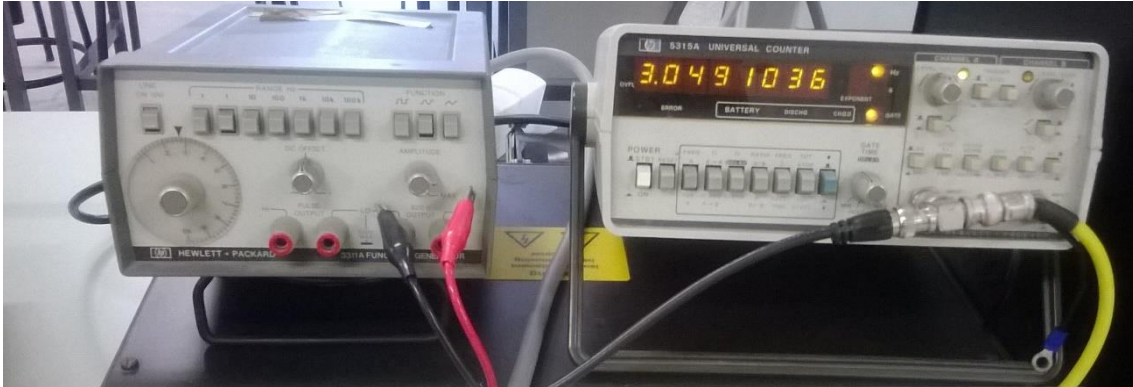


Figure 8 - Signal Generator (Left) and Universal Counter (Right).

Keeping the amplitude of the generated wave always constant, the frequency was progressively increased, from 0.5 Hz to 5 Hz, increasing 0.5 Hz on each step. The signal measured by the sensors is transmitted via Bluetooth to the PC where a program displays the original signal, the FFT of the signal (performed continuously on a 128 samples window), as well as the two main frequencies detected. The two main frequencies are displayed to be able to identify the peak frequency of the signal when the DC component (0 Hz) is bigger than the amplitude of the imputed signal by the PMS, this can happen since those operations were performed on an unfiltered signal (Figure 9).

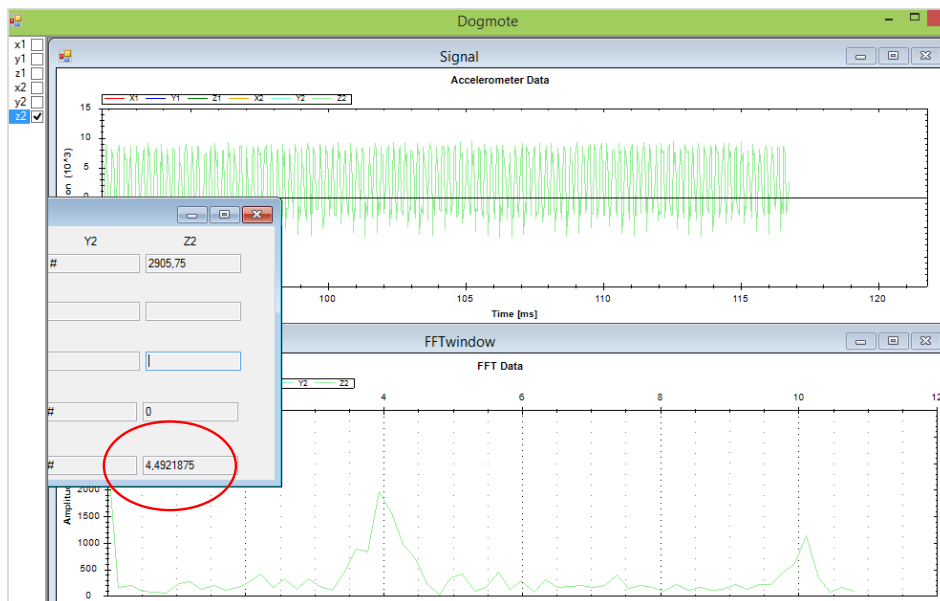


Figure 9- Example (@4.48Hz) of data acquired during the experiment. Original Signal (top), FFT (bottom), peak Frequency detected (encircled in red).

The results of this experiment, for every tested frequency, are shown in the table below (Table 2) where it is possible to observe the little difference between the inputted and the measured frequencies.

Table 2 - Tested Frequency (TF) Vs. Measured Frequency (MF). TF is the inputted frequency in the motor, and MF is the Frequency at which a spike is detected in the FFT performed by the PC.

TESTED FREQUENCY (HZ)	MEASURED FREQUENCY (HZ)
0,48	0,56
0,99	0,97
1,49	1,56
2,00	2,10
2,50	2,40
3,00	3,10
3,50	3,51
4,00	3,90
4,48	4,49
5,06	5,07

Having achieved the expected quality, some changes to the board had to be done in order to be able to proceed to the next phase of the project. Also, despite having obtained satisfactory results, some software problems were identified. The program became very slow after some time, or if selecting more than one signal do display, and sometimes it even froze or lost the connection. All of these problems were to be addressed in the next version of the program.

4.3. **Second Version**

After the first test, and needing to test the sensors on dogs, the breadboard and all the messy wiring on it needed to disappear. The fastest way to transfer the breadboard wiring and connections to a cleaner setup in order to be able to test it on the field, was to develop a shield for the Arduino Board.

4.3.1. Hardware

Main Components:

- (1) Arduino UNO;
- (1) JY-MCU Bluetooth Module;
- (2) MPU6050;
- (1) Perfboard;
- (1) 6xAA Battery holder.

To make the shield, connectors were placed to fit correctly on the Arduino board, and then the other connectors (for the Bluetooth (BT) module and for the sensors cables) were also soldered to a Perfboard, as shown in Figure 10. In this figure we can also see, in yellow and in red, how the 3,3V and 5V lines, respectively, are distributed on the board. The communication connections are shown in green (serial connection between the BT module and the Arduino, and I²C between the sensors and the Arduino).

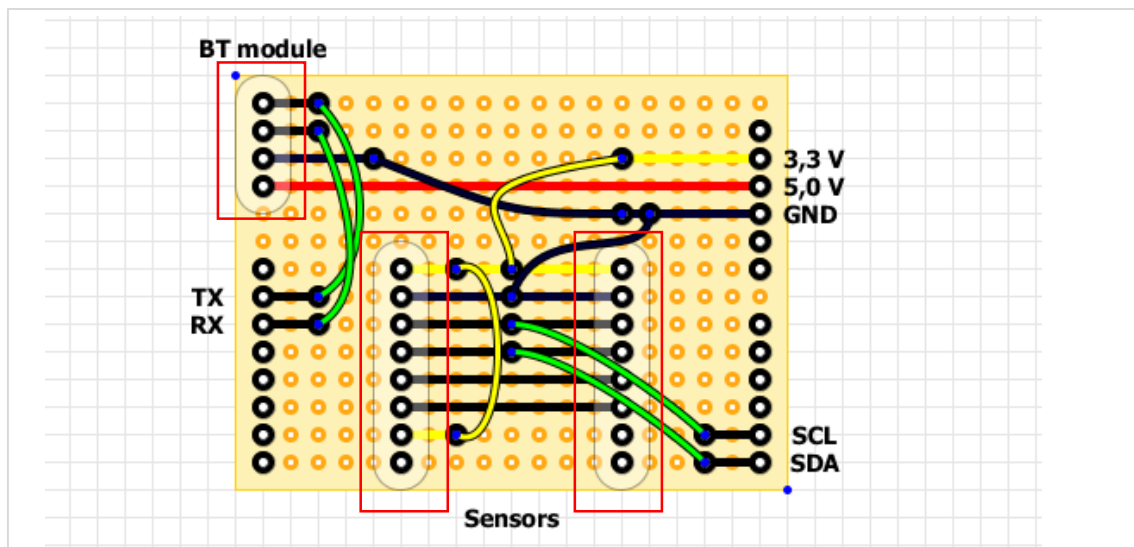


Figure 10 - Shield Schematic.

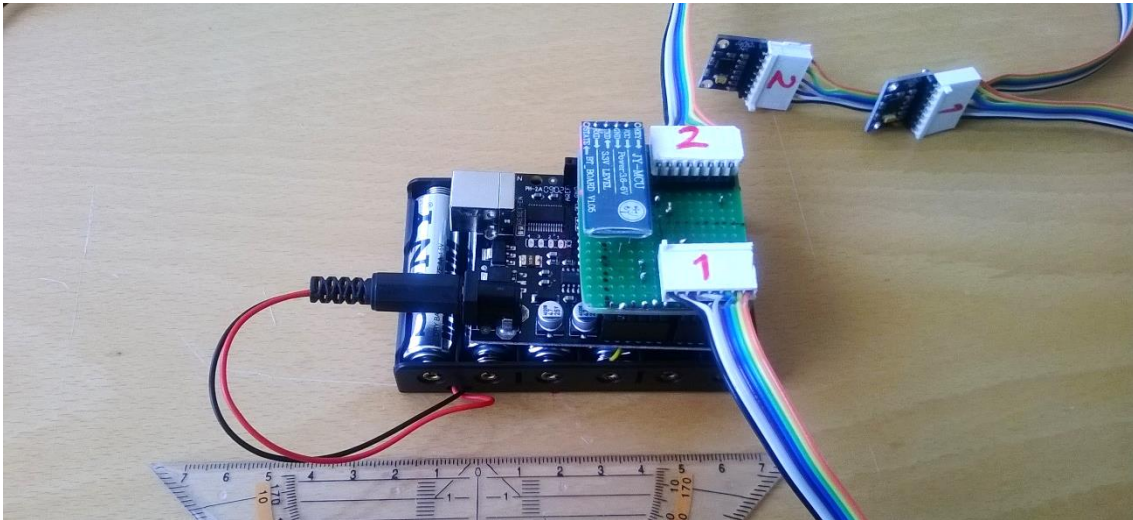


Figure 11 - Arduino with developed shield to connect the sensors and the Bluetooth module, and 6xAA batteries to power the ensemble.

Each connection was verified with a Multimeter before placing the shield on the Arduino Board, and before connecting the accelerometers and the BT module. After this, the board was powered and the VCC and Ground values of each header were verified (3,3V for the sensors, and 5V for the BT module). Then the BT module was added (Figure 11) and a test message was successfully received from the board. Finally the sensors were connected, and the values were also correctly received.

To protect the board, a small incasing was made using a Honey-Comb Polyethylene sheet and adhesive tape. The design used for the box is shown in Figure 12, where cuts were made afterwards to allow the connection of the sensor cables and the power source.

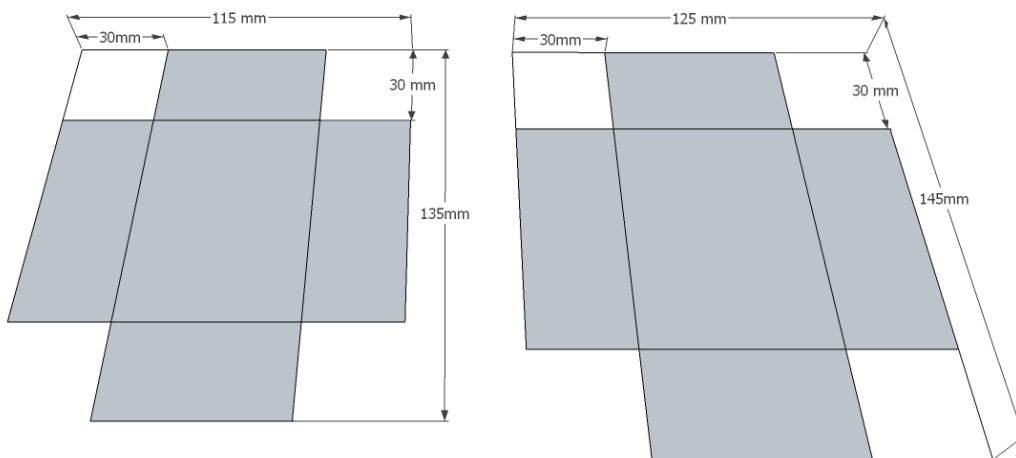


Figure 12 - Schematic of the protective Box made for the board. The base (left) and the cover (right).

The board was now protected against impacts (Figure 13), thus meaning that it was ready for its first real field test.

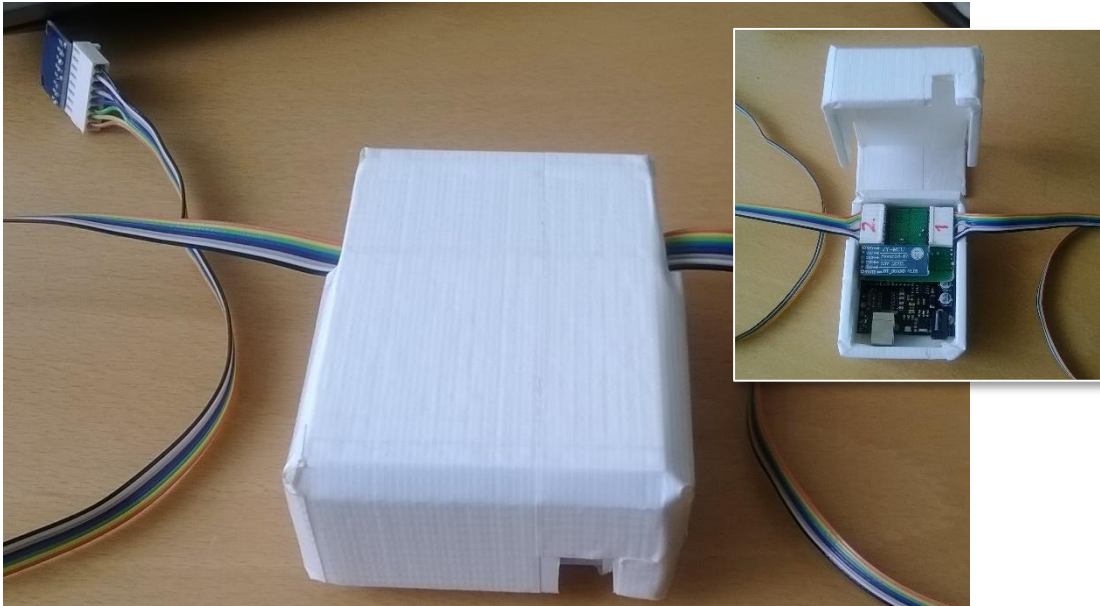


Figure 13 - The board inside the protective Box. Closed Box (large picture) and opened Box (small picture).

After this, the box still needed to be attached to the dog, and the sensors needed to be held on the correct position. For that, a simple Reflective Coat was used as support. The box and the sensors were attached to it using Velcro strips, as is shown in Figure 14.

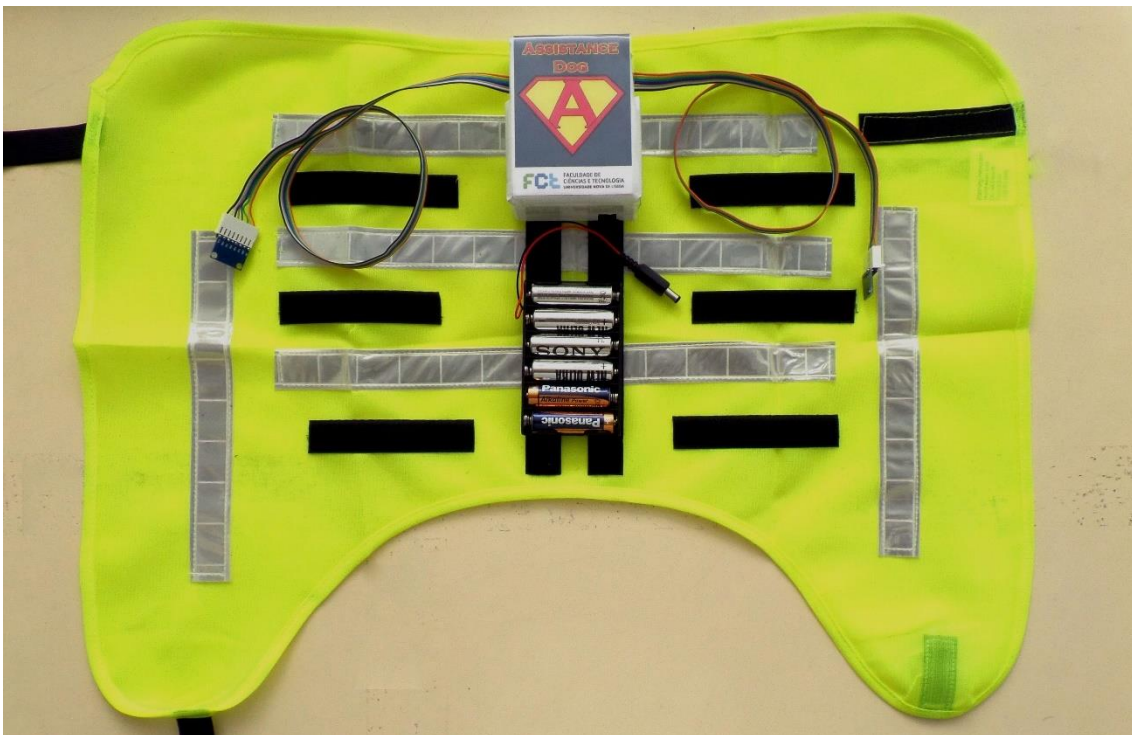


Figure 14 - Box, sensors and battery pack attached to the reflective coat using Velcro Strips.

However the software on the computer still needed to be improved before having the full system completely ready.

4.3.2. Software

In the previous version of the program some lack of responsiveness, freezes and disconnections were sometimes experienced. To solve this problems most of the program was completely rewritten in an effort to optimize a lot of the functions previously written, and also to take advantage of multicore processors found in most of today's computers by using paralleling techniques to speed up some commonly used functions. The user interface (UI) was mostly kept the same, but nonetheless some changes were implemented. The Analysis window that was previously detached from the rest was now integrated in the main window UI (feature 5, in Figure 15), and also includes information about the temperature read by the sensors. Still in the same window, some information that was shown previously in real time was now omitted (such as the signal Energy and Power), since it was considered secondary for this stage of the project, and because it could also help speeding up the program. Another change was the inclusion of more options in the axis selection field (feature 2, in Figure 15), and the addition of a filtering option, as well as some visual information about the status of the connection, recording and filtering (feature 1, in Figure 15).

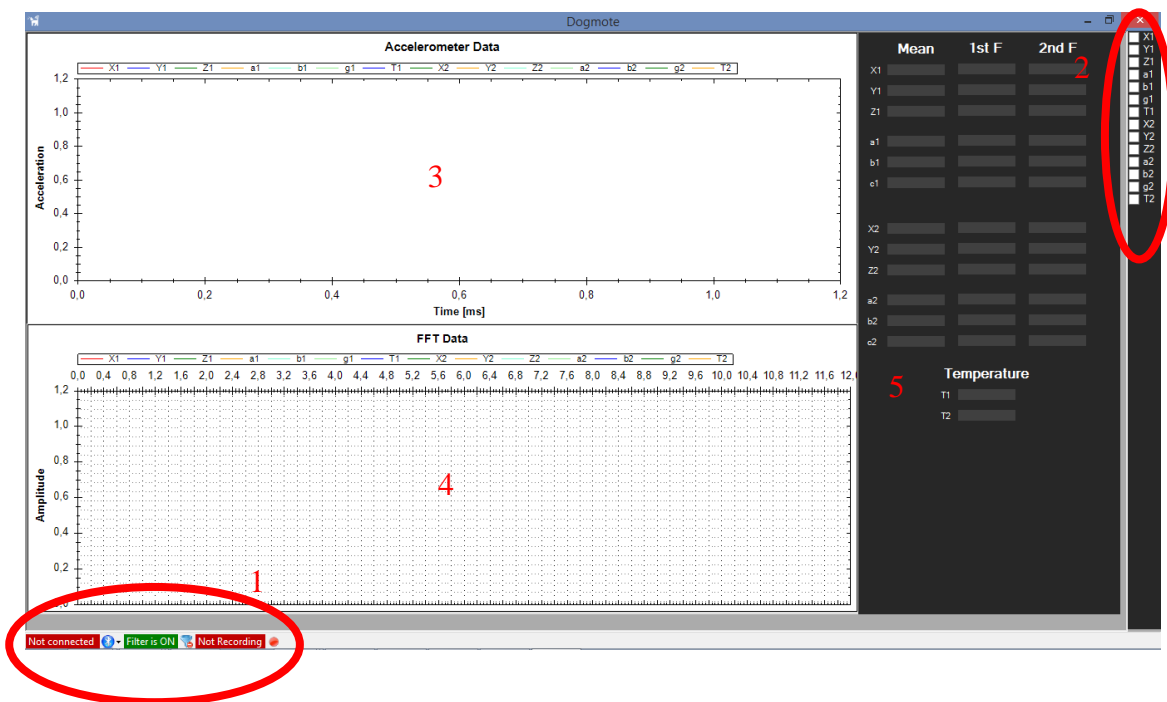


Figure 15 – Second application developed to assist during the sensors testing, with main features identified: 1 – connection options, 2 – Channel selection, 3 – Signal window, 4 – FFT window, 5 – Data Analysis window.

Having at this point improved both the hardware and the software, a new round of tests could now be performed.

4.3.3. Tests & Results



Figure 16 - Shiva with the device installed on her back.

The system was tested on two dogs. Shiva, a female Pit-bull, and Shrek, a male Boxer. One accelerometer was placed on each side of a dog's coat, while the board and batteries were placed in the center, as show in Figure 16.

The placement and orientation of the sensors were chosen so that it would be possible to use a common-mode rejection method to clean the signal of undesired movements, and to be able to amplify the respiratory movement (since the chest will expand in opposite direction on each side).The sensors on the dog were placed in such a manner that the accelerometers +X axis pointed to the front of the dog, the +Y axis pointed towards the floor, and the +Z axis pointed to the outside of the dog (in opposite directions), as depicted below in Figure 17.

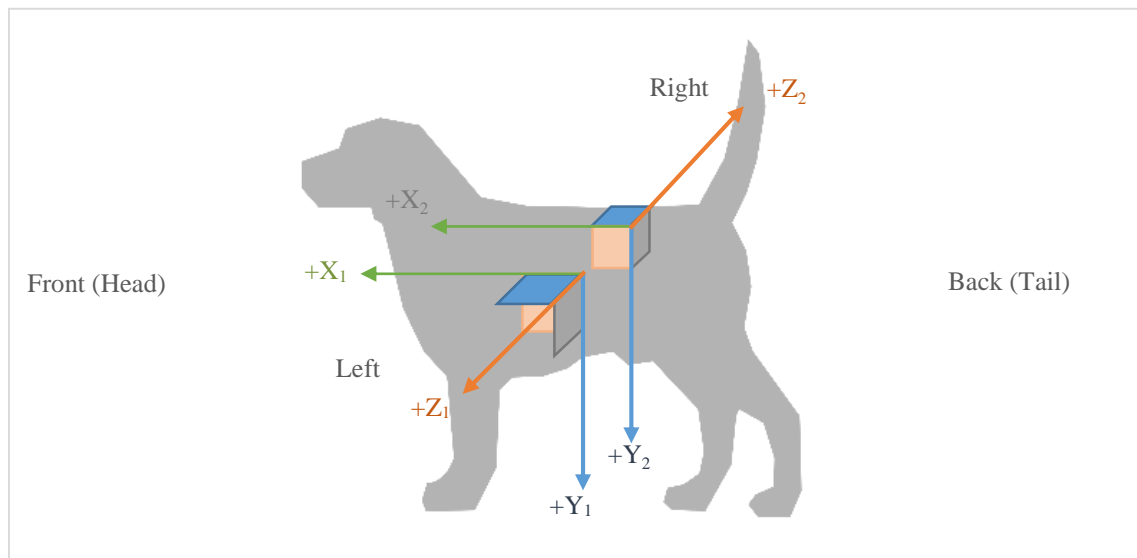


Figure 17 - Accelerometer axis orientation, as they were placed on the dogs.

The raw data from the sensors was recorded while one of the dogs performed some simple tasks: walk, run, seat and laydown. At the same time a video recording was made to correlate some of the data with real actions performed by the dog. The procedure was then repeated with the other dog.

Knowing the placement and orientation of the sensors, and in order to clean the signal, a Common-Mode Rejection method was used. In Matlab, the value of X1 and X2 were summed, as well as the values of Y1 and Y2, obtaining by that manner cleaner X and Y axis results. Similarly for the Z axis, Z1 was subtracted from Z2 (since they point in opposite directions on the same axis), obtaining also a cleaner Z axis measurement.

Observing the Y axis data, it was easily recognizable whether the dog was walking, running, or stationary. While stationary, it was also possible to determine if the dog was standing/laying or seating. The activity can easily be read through the signal amplitude (Figure 18), while the position can be read by Y+ vector amplitude value. If the dog is standing the vertical component (Y+) will be high because it is aligned with the gravity force vector, while in the seating position the Y component will make an angle with the same gravity vector, reducing the value that is read by the accelerometer (Figure 19).

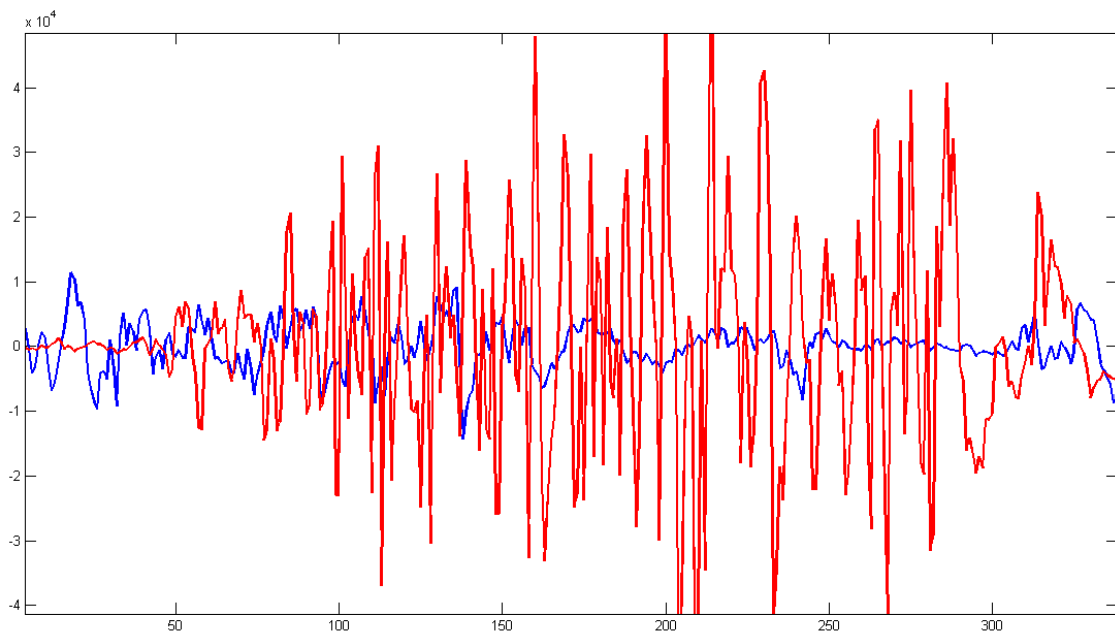


Figure 18 - Y Axis read by the accelerometers. Blue: Walking, Red: Running. [Signal length: 14s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)

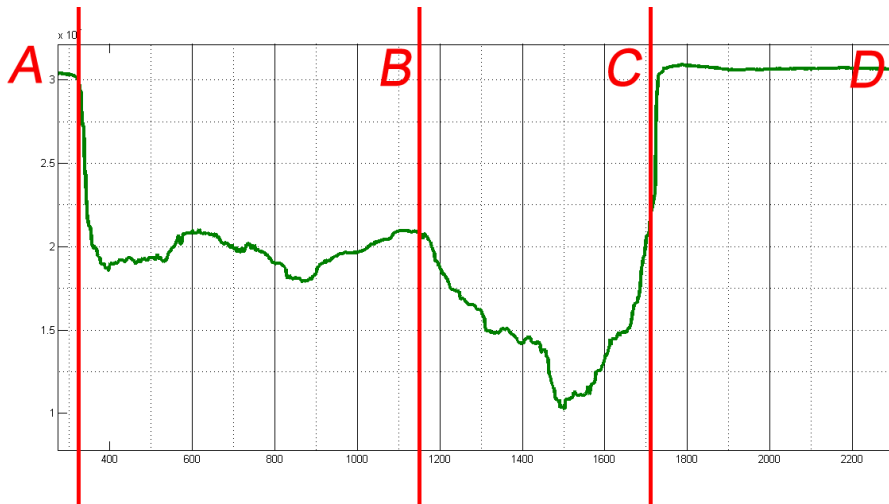


Figure 19 - Y Axis read by the accelerometer (Median). A: Standing, A-B: Seating, B-C: Seating more vertically, C-D: Standing. [Signal length: 1m 20s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)

On the other hand, the Z axis is better to provide the dog's respiratory rate, since the thorax of the dog moves outward and inward, simultaneously on the same Z axis but in opposite direction of each sensors, see Figure 20.

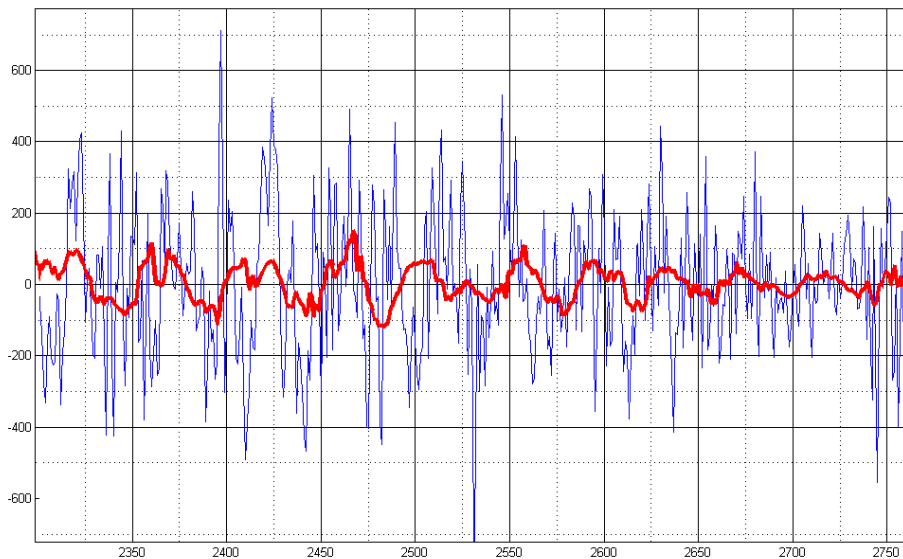


Figure 20 - Respiratory Rate. Blue: Z2-Z1 axis. Red: Median of the signal. [Signal length: 20s @25Hz]. (Vertical Axis: Amplitude; Horizontal Axis: Samples)

Analyzing the X axis data, a signal that could possibly correspond to a heartbeat was detected. Unfortunately both, respiratory and heart rate, signals are very low energy signals, and for that reason they are easily obscured by the movements of the dog, coat, or sensors. In order to confirm these results the experiment will be repeated, with some modifications.

4.4. **Third Version (Final)**

Since some robustness problems were encountered with the previous version of the hardware, different connectors and different cables ought to be used. It was equally desired to consolidate the microcontroller and the connectors on one board to minimize the components that can unplug them self, such as the shield. That hardware change led, further away, to a software change. A more fitted coat was also selected in order to minimize undesirable movements.

4.4.1. **Hardware**

Main Components:

- (1) ATmega328P (microcontroller);
- (1) JY-MCU Bluetooth Module;
- (2) MPU6050;
- (1) 6xAA Battery holder.

To solve the problems identified in the previous version, such as the shield unplugging momentarily if the dog made very abrupt movements, or the cables breaking after some time due to the stress induced by the constant movements of the dog, it was decided to use a CNC Router (a *Technodrill* C11000 with *GALAAD* software from *C.I.F.*) to mill a PCB on a copper sheet to integrate all the components possible in one board. The only component that was not integrated was the Bluetooth module since it would have unreasonably augmented the complexity of the project, and was for that reason deemed unnecessary for this stage of the project. Additionally, it was decided to use RJ-45 connectors and cables to connect the sensors to the board. This decision was made on the basis that RJ-45 cable are robust, easily repairable and easily replaceable if necessary since they are widely available everywhere.

Following that decision, schematics were created in Eagle from Cadsoft. The main board has as main component the microcontroller, and everything gravitates around it, as can be seen on Figure 21. On the top of the same figure, from right to left, we find the LED power indicator light, the 5V voltage regulator that powers the microcontroller and the Bluetooth module, and the 3,3V voltage regulator that powers the sensors. On the left of the microcontroller we find the reset button, and the external crystal oscillator that determines the operating frequency. On the right side we find the connectors for both sensors, as well as the connector for the Bluetooth module.

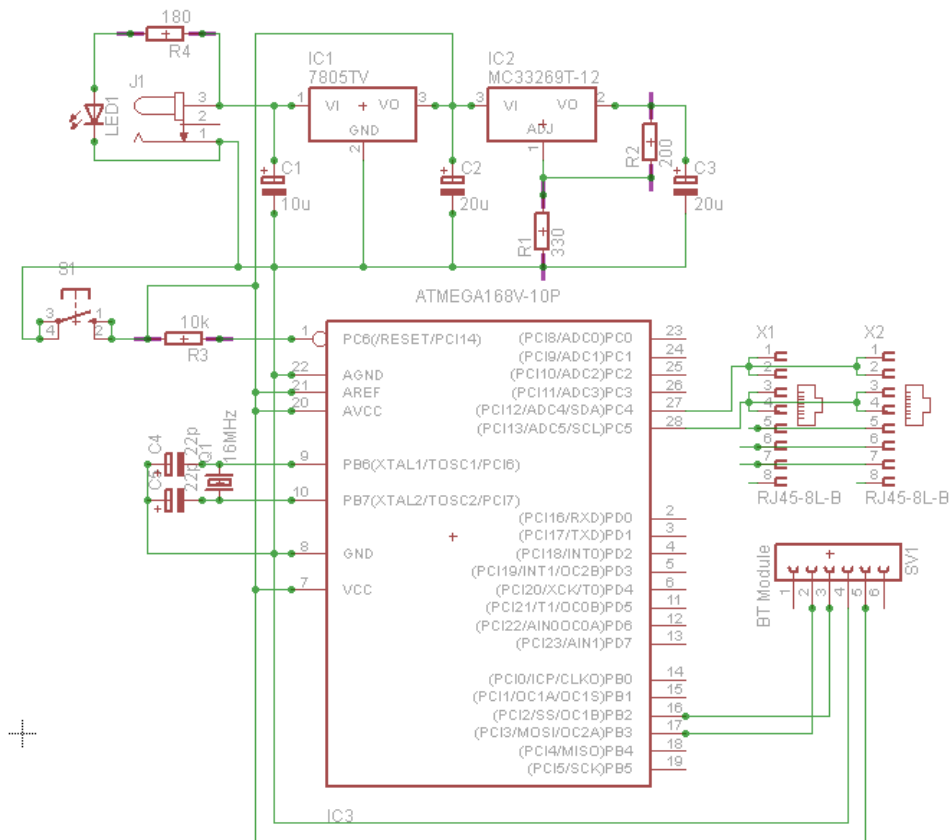


Figure 21 - Schematic of the developed board.

After the schematic is created, the board is generated by the Eagle software. The auto-router tools rarely produce adequate results, and for that reason the routes were manually designed, resulting in the board in Figure 22.

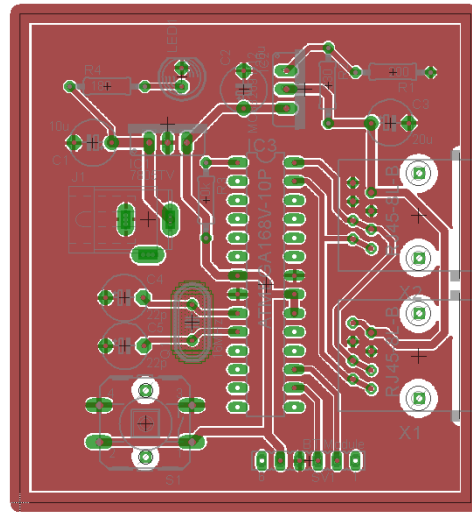


Figure 22 - Final board.

Having completed the design for the main board it was still necessary to create an adaptor between the sensors 8 pins and the RJ-45 plug. For that reason, another very small board was designed (one for each sensor), resulting in the schematic and board observable in Figure 23 (right and left side of the figure, respectively).

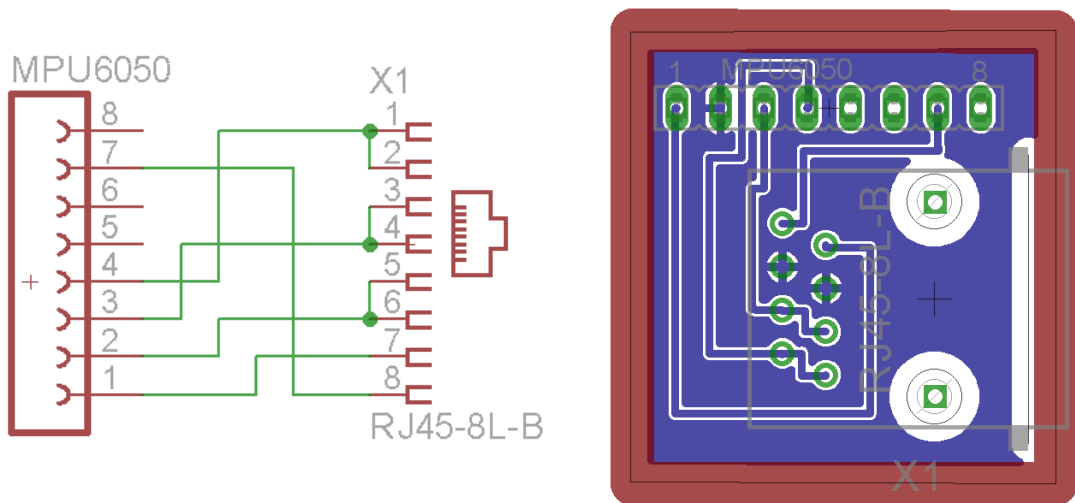


Figure 23 - Sensor/RJ45 adaptor schematic (left) and board (right).

The boards were then milled in the CNC router, and the components placed and soldered. Every connection was then checked one-by-one using a Multimeter to simplify any future debugging needs, resulting then in Boards show in Figure 24.

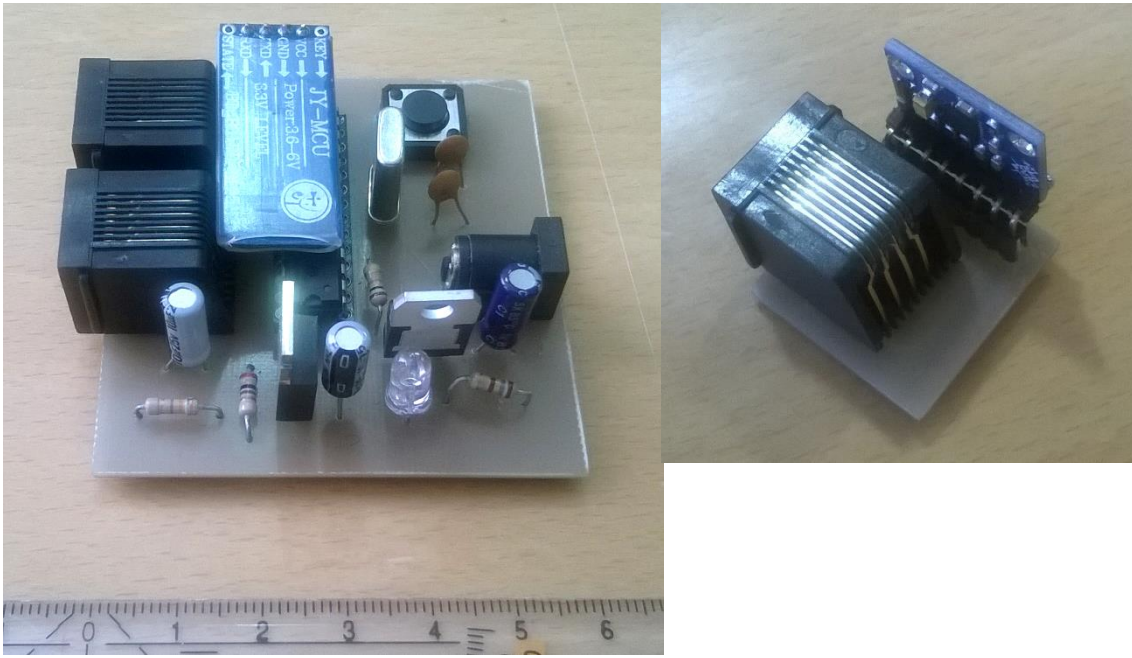


Figure 24 - Finished boards. Main board with Bluetooth module on the left, and adaptor with sensor on the right.

Finally a new box had to be made to fit, support and accommodate the main board. It was fabricated in Foamcore following the design on Figure 25.

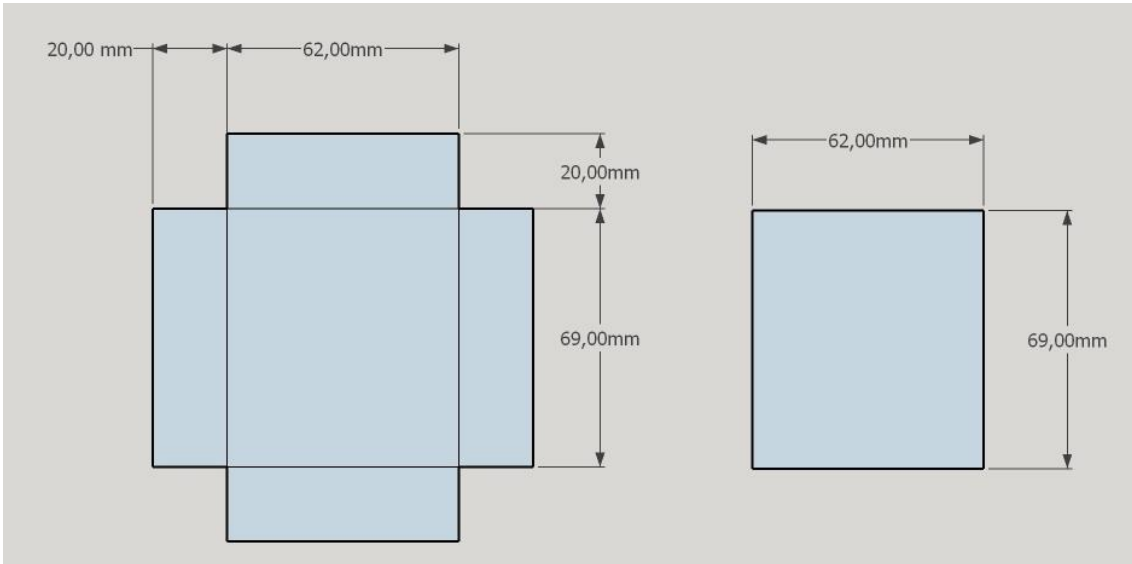


Figure 25 - Schematic of the protective Box made for the last version of the board. Base (left) and cover (right).

The box containing the main board, the battery pack and a small power on/off switch were placed on a Julius K9 IDC dog harness with Velcro strips (Figure 26).

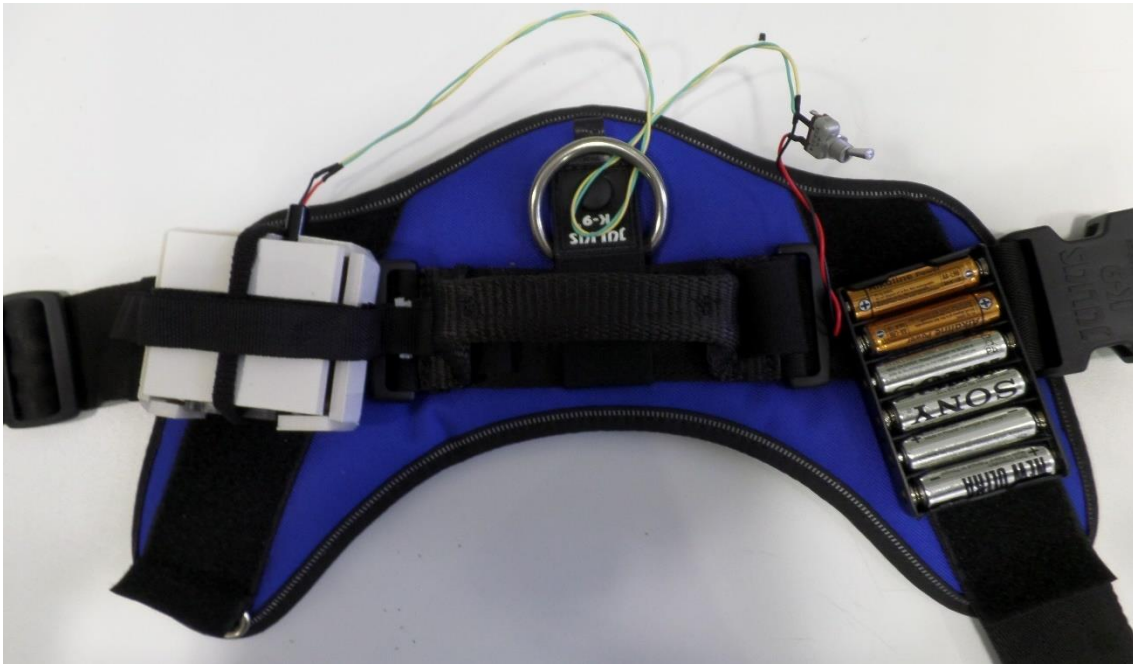


Figure 26 - Final system placed on the dog harness.

4.4.2. Software

During some initial tests the device did not seem to be responding as it should. There was a huge delay between readings and the device disconnected very frequently. Having already previously verified all connection on the board and sensor adapters, the problem could only be originated by the software. However since it was the same as previously used and no problems of this magnitude were encountered the problem had to come from somewhere else. Excluding the boards and the software, the only components left were the cables. Using a Multimeter the impedance of the cables was measured to about 100Ω , which is much more than the impedance of the cables used previously, that was measured to $2,5 \Omega$. It was then conjectured that the difference in impedance had to be slowing down the request (by the microcontroller) and the response (by the sensors) so much that it created conflicts. One of the solutions that came up was to accelerate the process between requests so that the probability of conflicts was reduced. With that in mind, it was decided to remove the implementation of the interrupts that was previously done and to replace it by a free and open source library for Arduino called *timer.h*. After some additional tests this seemed to have solved completely the problems that were initially encountered and it was now possible to carry on with the software improvements on the computers side.

Despite all the improvements done in the second version of the program, sometimes it still displayed some slowness and would sometimes lose the connection with the device. Having already optimized a good portion of the code the decision was made to abandon entirely the C# programming language and to start over from scratch in another programming language. After some research the decision was made to use Python since it is a light and efficient language, with plenty of free and open-source libraries. The main library that was used was PyQTGraph which is a Graphics and GUI library optimized for speed.

After some preliminary tests the results were very encouraging, and for that reason it was quickly adopted and the rest of the program converted to Python language. The GUI developed allows to observe the 3 acceleration axis from both sensors in real time, with an option from the context menu to observe the FFT of one or more axis at the same time, as it can be seen in Figure 27.

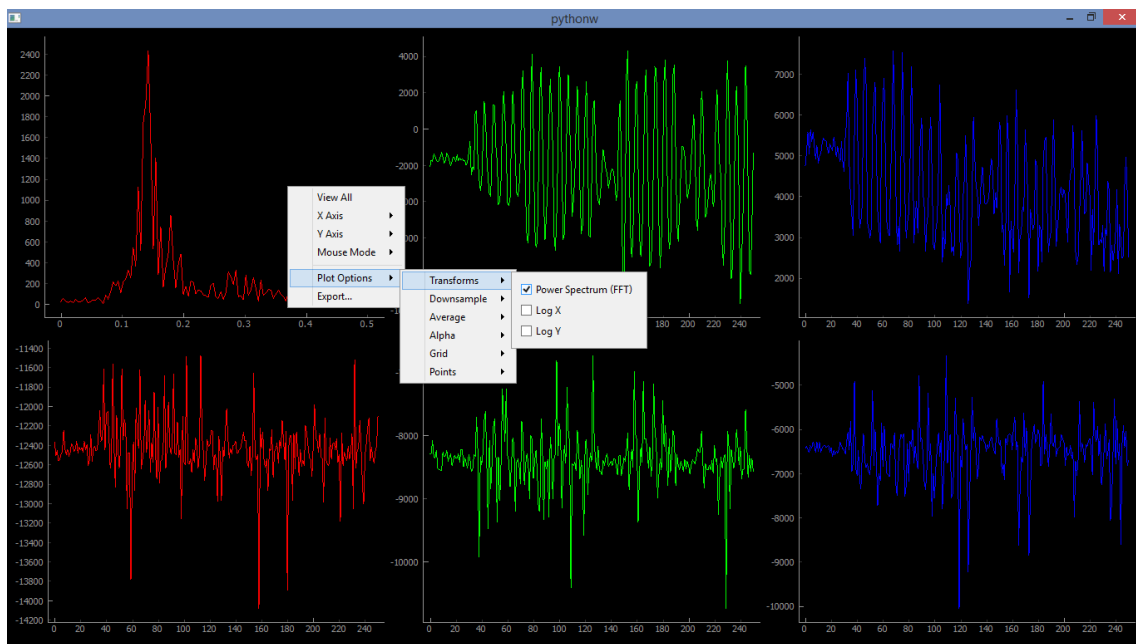


Figure 27 - GUI showing the data captured by the accelerometers in real time. In the top left signal, the option to display the FFT was activated.

Having solved all the slowness and instability from the earlier versions, the next step was to implement the detection rules based on the data resulting from the previous experience.

4.4.2.1. Activity Detection

Initially the mean value of the signals, and the amplitude (maximum value – minimum value) are calculated, and after that the following rules are applied:

If the Amplitude is < 10.000 then:

- a. If the mean is > 10.000 , the dog is **standing** still.
- b. Else the dog is **seating**.

Else, if the amplitude is < 50.000 , the dog is **walking**.

Else, the dog is **running**.

We can interpret the rules above as the following: If the dog is not moving very much, it is standing or seated, but if he is close to perpendicular to the gravity vector (the gravity is read by the sensor as 19.600), then it is standing and not seated, and vice-versa. If the dog is moving but not too much as to saturate the sensors, then it is walking, otherwise it is running. Visually this can be interpreted as show in Figure 28.

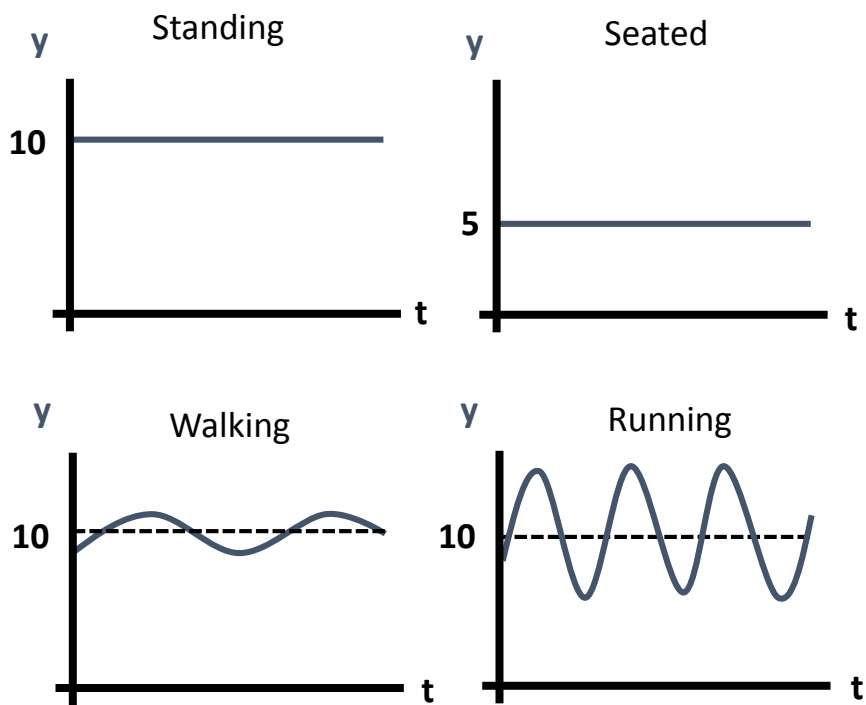


Figure 28 - Representation of the Activity identification rules.

4.4.2.2. Breathing Rate Detection

To detect the Breathing Rate the common-mode rejection property is used to amplify the respiratory movement and to attenuate any other unwanted movement (Figure 29)

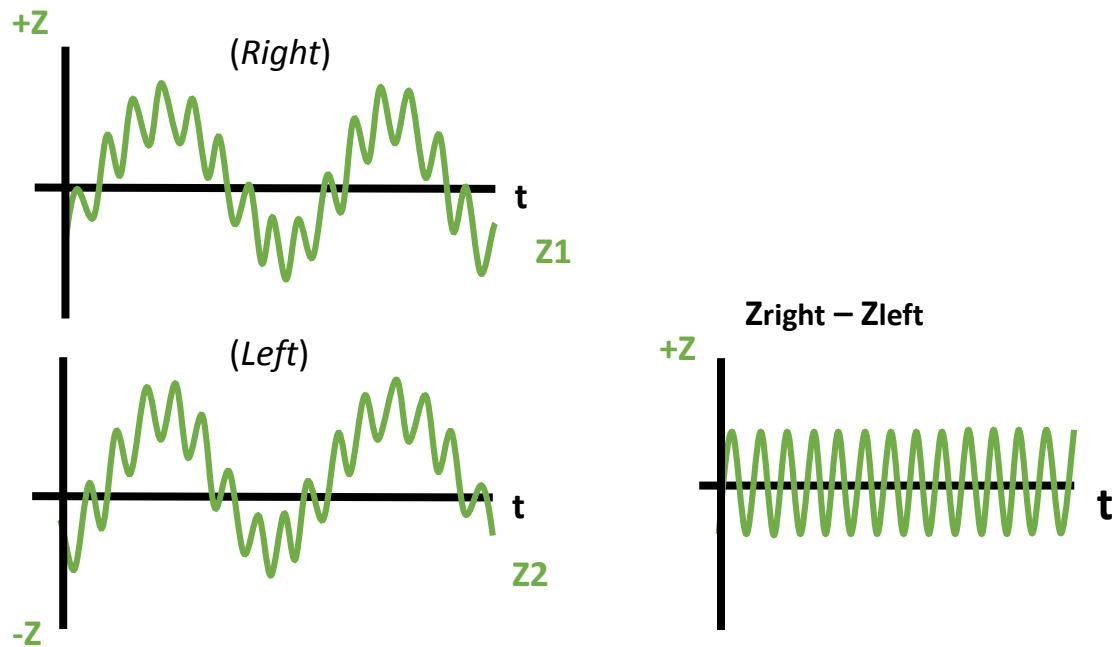


Figure 29 – Visualization of CMR.

This is done by subtracting the value read on the axis that point outwards (Z axis on Figure 17) by each one of the accelerometers on each side of the dog. That way the respiratory movement will show up as a small force exerted in opposite direction (chest expansion and contraction), while almost all forces that are exerted on the sensors due to movement show up in the same direction, and by subtracting these values it is then possible to retrieve the desired signal, without the interference from the other. Aside from that, a band-pass filter is also applied between 0,25Hz and 6Hz. Then, to detect the respiratory rate an FFT of the signal is performed over a 5 seconds window, and the frequency with the most energy is identified. That frequency corresponds to the respiratory rate.

4.4.2.3. GUI

Simultaneously, another GUI was developed, since the graphics displayed in real time are not very informative to the untrained eye and the data that we can extract has to be made available in an environment that is friendly to everyone, with any age.

For that reason, a virtual dog representation was modeled (Figure 30), rigged, and animated (Figure 31), using the software Cinema4D. The avatar shows what activity (in a caricatured way) is being performed by the dog in a very friendly and easy to understand manner, in real time. This aims to reinforce the owner's consideration for the information that is being displayed, especially for younger owners or family members.

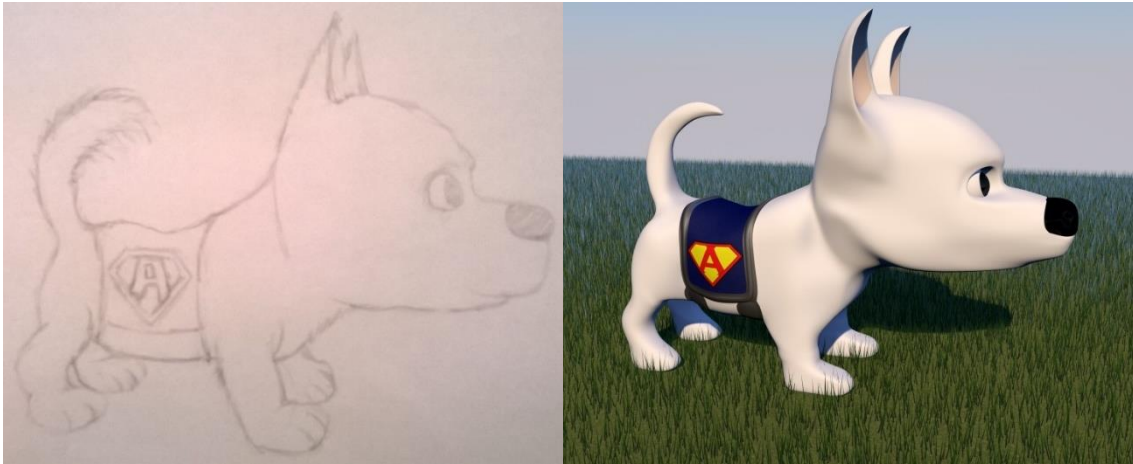


Figure 30 – Virtual dog representation. From drawing to 3D model.

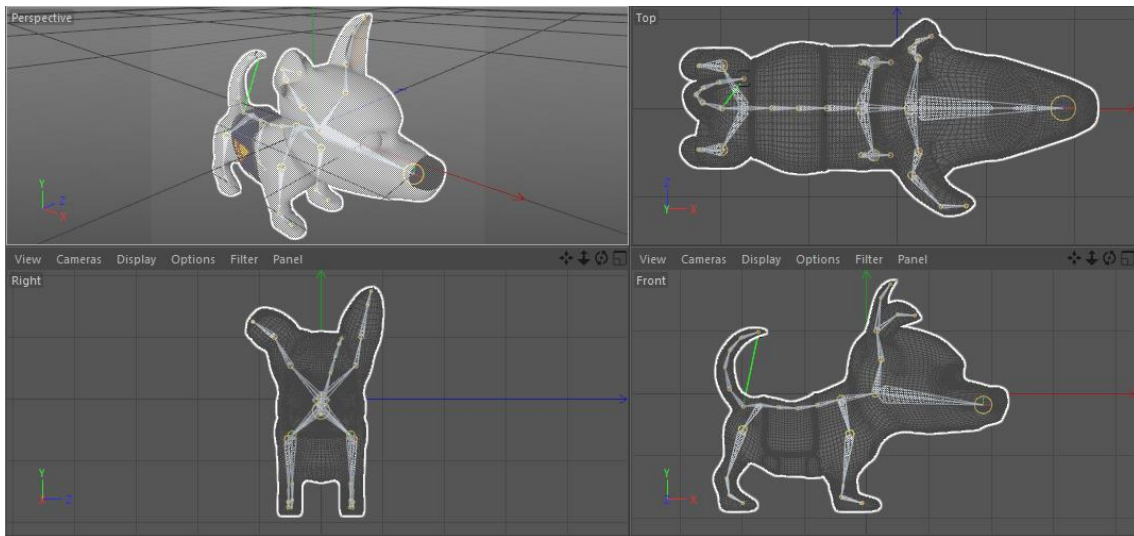


Figure 31 – Rigged model ready for animation.

To display the dogs activity a virtual environment was created in Unity3D, and exported to a web player so that in can be integrated in a standard webpage, the designated UI interface. This decision was made so that nothing had to be installed by the user (except the Unity3D plugin), and so that it can be kept always up to date without any user effort. The web interface also allows remote monitoring capabilities by the owner, a family member, a caretaker or by a veterinary professional.

The PHP webpage, besides displaying the avatar, also indicates in real time the dog's respiratory rate, as well as the environment temperature, as shown in Figure 32. The live information is auto updated using JavaScript.

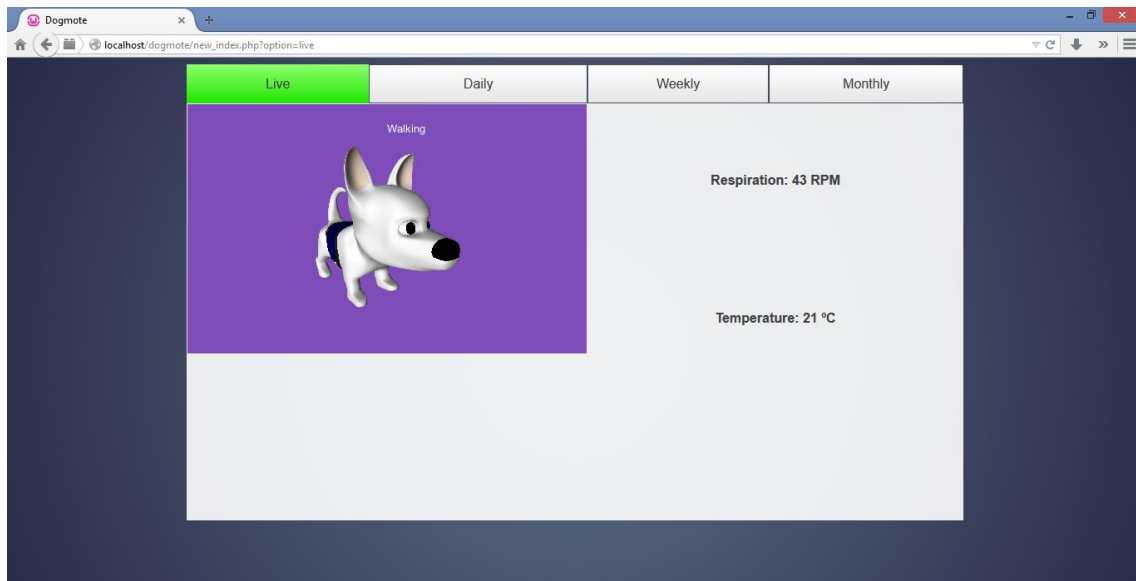


Figure 32 - Live information Window.

In addition to that live information, the user can also access three other tabs containing statistical information about the last 24 hours, the last 7 days, or the last 30 days, in the daily, weekly and monthly tabs respectively. On each of this tabs a pie chart showing the distribution of the dog's activities (as a percentage) along the chosen timeframe is displayed. Below that chart, another chart shows the evolution of the respiratory rate and of the temperature along the same timeframe previously chosen (Figure 33). This statistical information is automatically generated using the data that is periodically uploaded to the server's (MySQL) database by the Python script. The graphics are then created using JavaScript through Google Charts application programming interface (API).

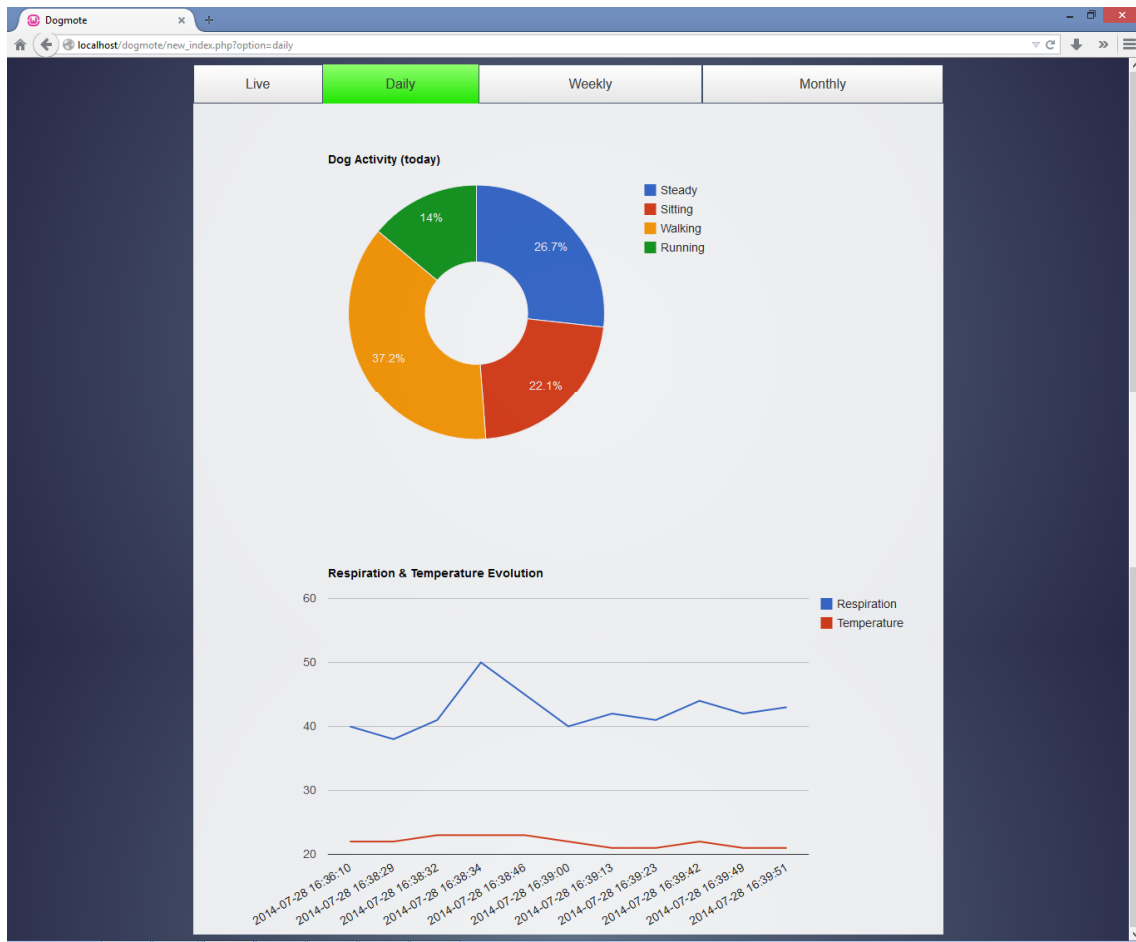


Figure 33 - Example of the statistics made available to the user.

Having finished all this hardware and software changes in this third – and final – version of the prototype, all was ready to another field test on dogs.

5. EXPERIMENTAL RESULTS

To test everything that was implemented in this final version, the system was installed again on the dogs (Figure 34) who were asked to perform a number of tasks, such as seating, running, walking and standing still.



Figure 34 - System placed on Shiva, a female Pit-bull.

5.1. Activity Detection

The activity detection algorithm, while the dog's transits from an activity to another, may in some situations detect the change accurately instantaneously, but in other situations it may need some more time to correctly identify the event, as summarized in Table 3. Nonetheless the algorithm gets a 100% accurate response after a maximum time equivalent to the rolling window time (defined to be 5 seconds in this experiment) on which the analysis is performed.

Table 3 - Activity transition Detection time.

From [↓] to [→]	Steady	Sitting	Walking	Running
Steady		Within 5s	Instantaneous	Instantaneous
Sitting	Within 5s		Instantaneous	Instantaneous
Walking	Within 5s	Within 5s		Instantaneous
Running	Within 5s	Within 5s	Within 5s	

5.2. Respiratory Rate and Heart Rate

Analyzing the logged data in Matlab and applying the algorithm explained in 4.4.2.2 but using a Wavelet analysis instead of the FFT, allowing to do a time-frequency analysis, it is possible to easily identify (by visual observation) the breathing rate, as can be seen in Figure 35.

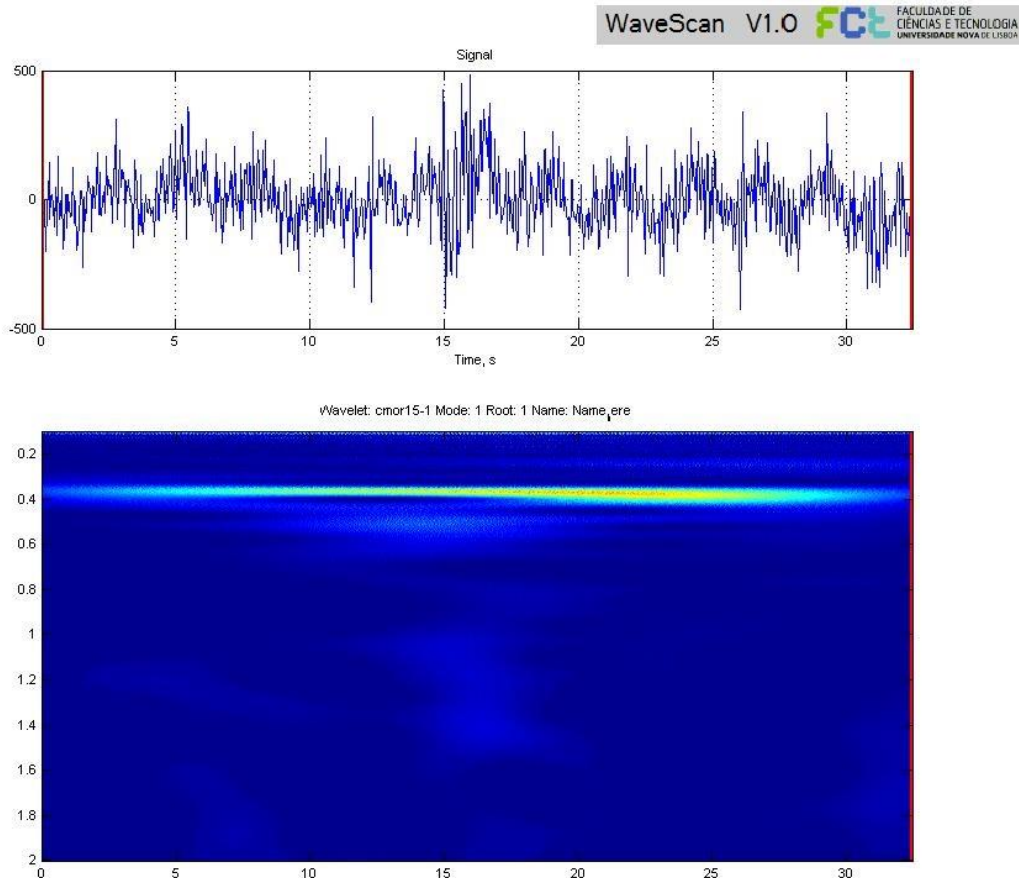


Figure 35 – Wavelet analysis of a portion of the signal logged during an experiment with the dogs.

Unfortunately this only works when the dog is not moving too much, meaning that the auto-detection algorithm should only try to identify the breathing rate when the dog is almost completely motionless. Also, albeit being able to do it visually at moments, the heart rate was not easily isolated from the noise, foiling the implementation of any automatic heart rate detection algorithm in this device. One way of overcoming this would be to augment the resolution of the data that is read by increasing the sample rate, but this leads directly to a waste of bandwidth and also to a misuse of processing power that is an important factor, especially for mobile and embedded applications such as this one.

5.3. Other Results

Alongside the results previously discussed, it is also important to note that the final version of the prototype was very robust and physically stable even in rough conditions such as the dogs rubbing against people, wet-dog shaking, or jumping, running and frolicking around.

Equally important, the device did not seem to bother or distract the animals in any way, despite the (unnecessary) long cables and the sensors not being in the most ergonomic shape or smallest form factor possible. Also worth mentioning, the GUI kept responsive throughout the experiment and provided accurate data both in real-time and for further analysis.

Price wise, the final board has a cost distribution as shown below in Table 4, with a final cost inferior to 30€.

Table 4 - Component cost distribution.

Component	Price ¹
MPU6050 accel/gyro	2*7,50 €
Microcontroller ATmega328P	1,50 €
JY-MCU BT module	5,50 €
PCB Copper board	0,75 €
RJ-45 8-Pin Connector	4*0,55 €
Other electronic components ²	< 5€ ³
TOTAL	< 30€

Similarly to the former development stages, this version could also be improved in many ways, as it will be discussed in the next chapter.

¹ Online prices with shipping included, as available in July 2014.

² Resistances, capacitors, oscillator, power regulators, led, and push button

³ These components were free for this project as they were donated by the University.

6. CONCLUSIONS & FUTURE WORK

The main purpose of this thesis was to develop a device that would be able to monitor the dog's health and activity continuously. While not all final applications of the project were accomplished in time, the results that were obtained allow us to understand that the correct approach was applied and that with more developing time, much more can be achieved from the device and techniques developed. Nonetheless, a fully autonomous wireless device that uses a totally non-invasive system was developed with the ability to provide real-time information in a very friendly interface, continuously, 24/7. To stress the fact that the whole system preserves the dog's comfort and natural behavior. Also very important, the low cost aspect of the device was successfully conserved, with a final cost of about 30€. The only main unachieved goal was the heart rate readings, which could be possible to achieve increasing the sample rate of the device but with the trade-offs that this implies.

This device may not only provide interesting information to the owner about the dog's well-being, but also provide essential information about the behavior and health of the dog in a long-term perspective, allowing the owner to observe small changes in behavioral patterns that would otherwise be invisible. This can also be very useful for ethologists that ambition to better understand all kind of animal's behaviors.

Despite all this project successes a lot more can still be improved, such as miniaturization of the boards using SMD components that would allow us to reduce the weight and size to at least a third of the current one. This step would also improve greatly the robustness of the device and its battery consumption.

Software wise, instead of using the unity3D plugin for the 3D avatar, a WebGL solution could be implemented. This would allow the interface to fully work in any PC or smart phone with a modern browser installed without the need to install additional plugins.

7. PUBLICATIONS & PRESENTATIONS

During this thesis, an article (in Appendix) was published with the following reference: Seabra, J., Rybarczyk, Y., Batista, A., Rybarczyk, P., Lebet, M.C., and Vernay, D. (2014) "Development of a wearable monitoring system for service dogs." IEEE Roman'14, Workshop on Wearable Technology and Human-Wearable Robot Interaction. Edinburgh, UK, 25th of August.

This article was presented in IEEE Roman'14, Workshop on Wearable Technology and Human-Wearable Robot Interaction in Edinburgh, UK, on the 25th of August.

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