Universidade de Aveiro
Departamento de
Eletrónica, Telecomunicações e Informática
2014

Joana Rodrigues Garrido

TURF: Solução para localização de bombeiros em incêndios urbanos

TURF: A low cost solution for Tracking firemen in Urban Fires

"Give me six hours to chop down a tree and I will spend the first four sharpening the axe"

Abraham Lincoln

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TURF: Solução de baixo custo para localização de bombeiros em incêndios urbanos

TURF: A low cost solution for Tracking firemen in Urban Fires

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Manuel Bernardo Salvador Cunha, Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e sob a coorientação científica do Doutor João Paulo Trigueiros da Silva Cunha, Professor Associado com Agregação ao Departamento de Engenharia Eletrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto.

Dedicatória

Dedico este trabalho aos meus pais, à minha irmã, ao meu namorado e à Graça Lemos.

O júri

Presidente	Prof. Doutor José Manuel Matos Moreira Professor. Auxiliar da Universidade de Aveiro
Vogais	Prof. Doutor Jorge Augusto Fernandes Ferreira Professor Auxiliar da Universidade de Aveiro
	Prof. Doutor Manuel Bernardo Salvador Cunha (Orientador) Professor Auxiliar da Universidade de Aveiro

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Palavras-chave

Bluetooth, combate a incêndios, incêndios urbanos, localização, sensor de infravermelho, sensor de ultrassom, TURF, VitalResponder

Resumo

Em cenários críticos de emergência, as equipas de resposta são submetidas a situações de *stress* e risco extremamente elevados. Para os ajudar a reagir, deu-se início ao projeto *VitalResponder* que é atualmente capaz de monitorizar continuamente os sinais vitais dos bombeiros devido à tecnologia embutida nos seus fatos. Este sistema fornece ao comandante de operações a capacidade de avaliar as condições de saúde dos seus bombeiros e agir de acordo com as suas necessidades.

A localização de bombeiros é um fator muito importante em situações de incêndios urbanos. Devido às fracas condições de visibilidade e comunicação, é essencial que cada bombeiro tenha noção da posição dos seus colegas por questões de organização e salvamento.

O objetivo desta dissertação é construir um sistema simples e de baixo custo, que será incorporado no projeto *VitalResponder*, e fornecerá informações acerca da presença de um bombeiro ou uma parede e a sua respetiva distância. A solução mais simples para este problema é utilizar fusão sensorial de um sensor infravermelho, para distinguir uma parede de um bombeiro, e um sensor de ultrassom, para medir a distância ao obstáculo/colega.

Keywords

Bluetooth, firefighting, infrared sensor, tracking, TURF, ultrasound sensor, urban fires, VitalResponder

Abstract

When in critical emergency scenarios, first responders are submitted to highly stressful and risky situations. In order to help them dealing with these conditions, the *VitalResponder* project started and is now capable of continuously monitor the vital signs of firemen with wearable technologies. This provides to the chief of operations the capability to evaluate the health conditions of his firefighters and react according to their needs.

The localization of firemen is an important factor when dealing with urban fires. Due to low visibility and difficult communication conditions, is essential for each fireman to be aware of his colleagues' whereabouts for organization and, in case of need, rescue matters.

The idea behind this dissertation is to build a simple and low cost tracking system, embedded in the *VitalResponder* wearable technology, which can give information about the presence of a fireman or a wall and its distance. The simplest answer found to this problem was sensor fusion using an infrared sensor, to distinguish a wall from a fireman, and an ultrasound sensor, to provide the distance to the obstacle/colleague.

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List of Acronyms

ECG	Electrocardiogram
ERT	Emergency Resource Tracking
GLANSER	Geospatial Location Accountability and Navigation System for Emergency Responders
GPS	Global Positioning System
IEETA	Instituto de Engenharia Eletrónica e Telemática de Aveiro
IMU	Inertial Movement Unit
IR	Infrared
LDO	Low Dropout
MEMS	MicroElectroMechanical Systems
NEP	Noise Equivalent Powe
PCB	Printed Circuit Board
PIR	Passive Infrared Sensor
PPG	Photoplethysmography
RFID	Radio Frequency Identification
RTLS	Real Time Location System
RX	Receive
TURF	Tracking fireman Urban Fires
TX	Transmit
UHF	Ultra High Frequency
USA	United States of America
USB	Universal Serial Bus
VJ	VitalJacket®

Chapter One

Introduction

The present dissertation describes an innovative system for tracking firefighters in urban fires. It is divided in six chapters, each of them separated into several sections for organization matters.

This first chapter introduces the dissertation, by briefly framing the TURF system in the *VitalResponder* project and presenting the goals to achieve.

The second chapter has three sections. The first one will explain the technology available for localization, tracking and identification. The second section references devices already existent in the market or under development for firemen localization/tracking in urban fires. The third section explains with some detail the *VitalResponder* project, its motivation and the developed technology.

The third chapter is combined in two main sections: Hardware and Software components. The first section describes all the used hardware devices, its functioning and consumption. The second section presents the software operation timing, the Bluetooth and Android communication.

The fourth chapter addresses the operational setup of the TURF system and the testing conditions. It also includes the test results of the field performance of TURF. A detailed analysis of the results finalizes the chapter.

Lastly, the fifth chapter will conclude this dissertation by showing the viability of the system through a brief analysis of the tests performed and if can indeed be made and used by the firefighters. This chapter also points out some aspects that needed to be improved in the future.

1.1. Motivation and Context

According to the Washington Military Department, an urban fire is an “uncontrolled burning in a residence or building from natural, human or technical causes” [1]. Most commonly, this type of fires is caused by humans, a fireplace, a stove or even a candle can start it. Furthermore, urban fires usually begin in the main divisions of a house, where more furniture and textiles are present, making the fire to spread rapidly.

Urban fires must be extinguished the fastest way possible to avoid the spread to the adjoining structures, increasing the consequences and difficulty of extinction. Having this in mind, firemen have to act fast to save people's lives and avoid complications. By doing so, they are submitted to highly stressful and dangerous situations.

Trying to improve the quality of life of these men, a research team got together and start developing a project, *VitalResponder* [2], to prevent dangerous situations and to improve the efficiency and time response in rescuing scenarios. Based on the *VitalJacket*® [3] system, already existent, it became possible to continuously monitor the vital signs of firemen to “provide secure, reliable and effective first-response systems in critical emergency scenarios”. This wearable technology acquires individual data including ECG, location (GPS) and physical activity (accelerometer), which are sent via *Bluetooth* to the *DroidJacket* [4] application that is able to process the ECG data, extract pulse information and heartbeat characteristics. Since some health problems, as arrhythmia, aren’t perceivable with just a few seconds of analysis of the ECG signal, the *VitalResponder* system monitors the heart during a long period of time, making it possible to detect some major health events. Leveraging this information, the operation’s commander has a device running *DroidJacket* and if he sees that one of his man is not responding properly to the stress or smoke, an order is sent and that fireman is taken out of the emergency location.

The system developed so far acts as preventive method but one must think about the case where the fireman is actually in danger and can't make it out of the building. To solve this, an improvement to *VitalResponder* must be performed to keep track of firefighters.

Two conditions must be kept in mind during this process:

1) Portability: the extra equipment must be placed on the fireman so no time is wasted settling the new system;

2) Price: since the firefighters’ corporation budget is limited, the cheapest the system is, the easiest is to be introduced in a considerable scale.

Since this project has an important practical scope, the opinion of the firefighters was taken into account and the system's characteristics were discussed in an interview with the commander of Águeda's corporation.

1.2. Goals

Urban fires are characterized by weak communication conditions but the low visibility is the main cause of problems in firefighting. When the smoke is very dense, it becomes easy to lose one's orientation and is impossible to know the location of the obstacles or the team mates. The *VitalResponder* project is now presenting a solution for this particular problem, TURF – Tracking firemen in Urban Fires.

The main goal of this dissertation is to build a system using low cost and simple sensors, wearable and integrated in the firemen's equipment. The TURF system will be composed by an infrared (IR) and an ultrasound sensors. These were the chosen sensors based on an extensive research presented later in the second chapter. One example of these studies is the evaluation performed by Schubert et al. [5] that obtained satisfying results for the selected sensors.

This system will allow the co-tracking of firemen by providing distance and identification of an obstacle. As known, urban firefighting is a team procedure, normally provided by four elements, aligned along the hose. With this formation, our system tries to track the man in front (Figure 1). Each firefighter carries an infrared emitter that allows team mates' equipment to distinguish him from any other type of static obstacle. This allows the TURF system to identify possible dangerous situations, namely the absence of its nearest colleague, ahead of him in the fire combat line. When the IR signal is received, the ultrasound device can provide a measurement of the distance between the fireman and the teammate/obstacle in front of him. This information can be provided to the fireman himself via radio.

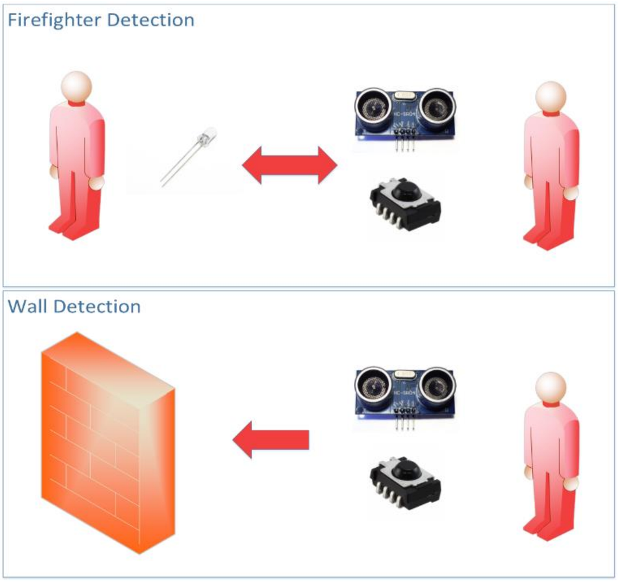


Figure 1: TURF Identification Principle

This dissertation describes the hardware and software associated to the TURF system. It's also presented the Android application that displays the hardware data to the end user, transmitted via Bluetooth.

The overall system will be submitted to real scenarios to prove the concept.

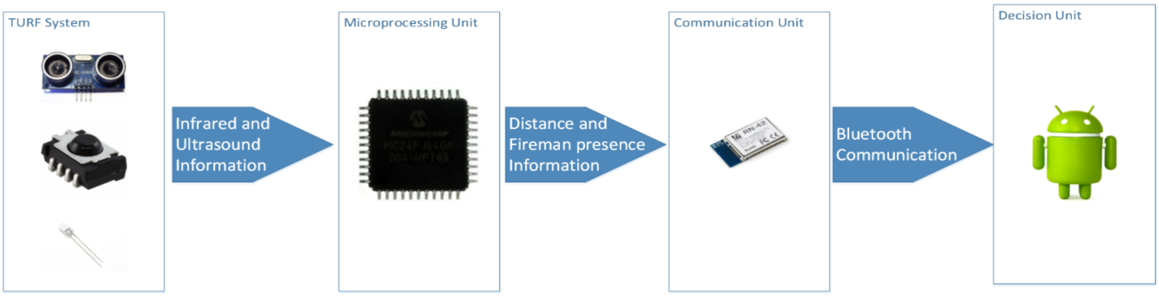


Figure 2: TURF Data flow diagram

Chapter Two

State of the Art

Tracking firefighters in fire situations, especially urban fires, has been an issue under study for many years. There are several technologies available to achieve this goal, all of them giving different information. When combined they make it possible to know the location, movement, distance and so on.

This chapter is organized in three sections. The first section, Tracking and Location Sensors, presents some of the sensors and technologies, advantages and disadvantages for its use in firefighting.

The second section, Sensor Fusion Systems for Firefighting, describes the main systems developed for urban and forest firefighting using the technologies mentioned in the first section.

The last section is about the *Vital Responder* Project, providing an analysis of the goals, technologies and results obtained so far. The TURF system can be integrated in the *VitalResponder*, this is an important section to frame the reader in the context of the project.

2.1. Tracking and Localization Technologies

2.1.1. Ultrasound Sensor

Ultrasonic sensors are based on the analysis of the propagation of waves for frequencies higher than 20 KHz.

An ultrasonic sensor is composed by two transducers, responsible for the conversion of the energy in ultrasonic waves and vice-versa. These two devices function as a transmitter and a receiver, where the first sends a high frequency pulse and when this reaches the object, the wave is reflected back to the receiver. When it arrives, the time that it took to go from and come back to the ultrasonic sensor is computed. Finally, the time must be multiplied by the velocity of sound, since the distance is the desired unit and divided by two because the time obtained is from the round trip.

$$Distance\ (m) = \frac{Sound\ Velocity\ \left(\frac{m}{s}\right) * Time\ (s)}{2} \qquad (1)$$

This type of sensors detect liquid levels, clear objects and high reflective or metallic surfaces.

On the other hand, ultrasonic sensors are susceptible to temperature, since as it increases, the sound waves travel faster to and from the target. The air temperature affects the elastic properties of the air particles, i.e., the tendency that a material has to keep its shape when induced by a force or stress. Since the sound waves propagate based on a particle to particle interaction, if these air particles can't preserve their properties with temperature variations, the waves' propagation is going to change as well [6].

The wind is also a concern for this kind of sensors since it can create an invisible barrier that will lead to a false measurement [7].

When using ultrasonic sensors, one must keep in mind that these have a dead zone of approximately 30 cm, depending on the sensor, making it impossible to measure distances to very close objects. Moreover, these sensors don't measure only in front of them, having an area (usually 30°) where objects can be detected (Figure 3). This is due to the relation between the diameter of the transducer when compared to the wavelength of the sound at the operating frequency, D/λ [8]. The larger the diameter of the transducer as compared to a wavelength of sound, the narrower the sound beam. In this case, the diameter is twice the wavelength.

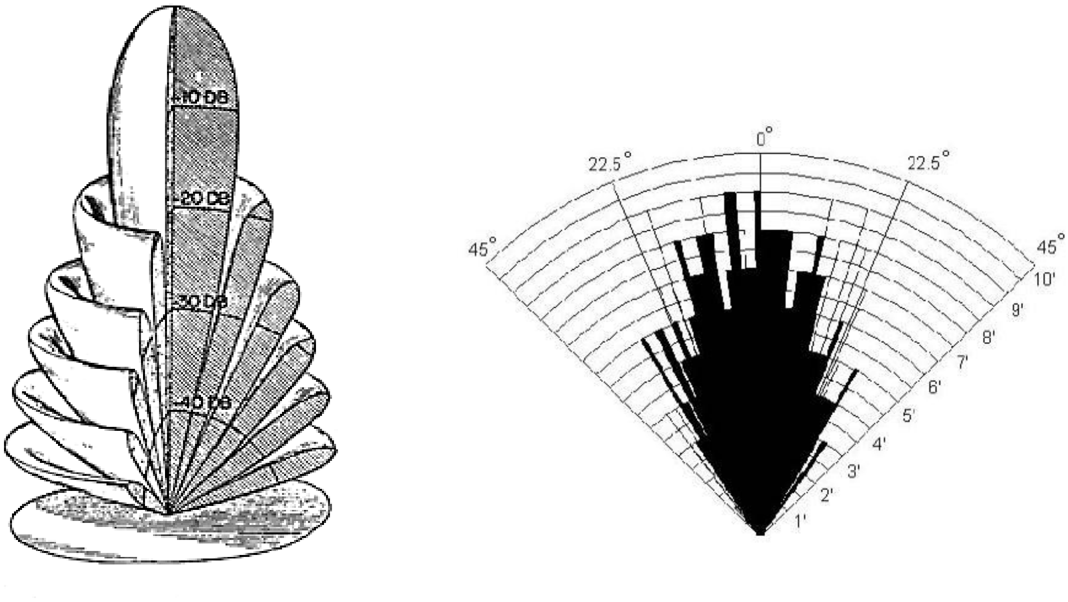
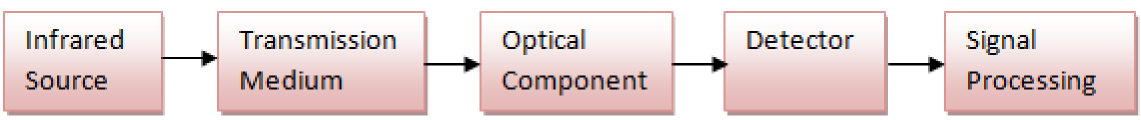


Figure 3: Radiation Diagram [8] (Left) and Angle of detection of Ultrasound Sensor [9] (Right)

The possibility of using this type of sensors for urban firefighting is being evaluated and has obtained promising results. Some of the systems under study are shown in a later section.

2.1.2. Infrared Sensor

The infrared sensor pair takes advantage of the body and surfaces characteristics to collect data. The infrared radiation (0.75 µm and 1000 µm) is invisible to the human's eye since its gamma has higher value than the visible radiation and smaller than microwave radiation. A typical system for infrared radiation is composed by the elements pointed in the following diagram [10].



An **infrared source** can be composed by an infrared light source or a body with temperature above 0 K. The **transmission mediums** for infrared radiation are vacuum, atmosphere and optical fibers. The **optical components** are required to converge or focus infrared radiation, limiting the spectral response. When choosing an infrared **detector**, there are several factors that need to be taken into account as photosensitivity or responsivity, noise equivalent power (NEP) and detectivity. Finally, the **signal processing** is used to amplify the received signal for a better analysis of the results.

In the scope of this dissertation, is worth to mention that infrared radiation is already used in firefighting situations, mainly in infrared cameras. This subject is detailed in a later section.

2.1.3. GPS – Global Positioning System

GPS (Global Positioning System) was designed by the USA Department of Defense and is a satellite-based navigation system. It provides the location and time information through 27 satellites (24 operational satellites and 3 extra in case some of the others fail) placed around the Earth. GPS is only functional with four or more in line of sight satellites, so this will not work inside buildings, for example.

The first goal was to make GPS available for military use only but it was provided to all civilians and is now workable under any weather conditions, anytime, worldwide and it's free of charge.

GPS uses three components:

- The space satellites: 24 satellites that circle the Earth twice a day in a very precise orbit;
- A control unit: there are a master control station and an alternative one, four dedicated ground antennas and six monitor stations. This unit guarantees the good functioning of the satellites;
- A user receiver: composed by an antenna tuned to the same frequency as the satellites, a high stability clock (crystal oscillators) and a processor. It can have a display to show the position and velocity or send the information to a database.

The satellites send time information to the receivers on Earth. After obtaining the information, they use triangulation to compute the difference between the time sent by the satellites and its own time. For this to work perfectly, both the receiver and satellite clocks need to be synchronized with a nanosecond precision.

It's impossible to use GPS systems in fires occurring in indoor scenarios since there are no satellites in line of sight. But it can be very useful when dealing with forest fires.

Nowadays, GPS technology is used in a number of applications in this context. An application example is the firefighting aircraft [11] , where GPS controls the position of all the airplanes that are fighting that fire, avoiding them to collide, providing the location of the target and the places where water is needed.

In a large scale fire, it is more difficult to control it. If the receivers are placed in the perimeter of the fire, it's possible to know its extent and mapping it. When GPS information is complemented by another source, it's possible to provide topographic information, like valleys, hills and type of vegetation. Also, when backup is required, the closest emergency members are called and it is given an exact location for them to go [12].

Finally, GPS provides the exact location of all the fire trucks and vehicles, which presents itself as an advantage for management of the resources at a scene.

2.1.4. RFID – Radio Frequency Identification

Radio Frequency Identification is a method of automatic identification through radio waves. The device consists of a small chip, capable of storing a maximum of 2 Kbytes of data, and an antenna. This set is called RFID tag. The antenna enables the chip to transmit the identification information to a reader that will convert the radio waves sent by the RFID tag into digital information to be used.

RFID came to replace magnetic strips on the credit cards and bar codes. One of the advantages that contributed to this replacement is the fact that the chip doesn't need to be perfectly positioned relatively to the scanner.

The usage of RFID has two adjacent problems: tag and reader collision. In the reader collision, the signals from more than one reader overlap and the tags can't respond to the simultaneous queries. The tag collision happens when several tags are placed in a small place. The last problem is simpler to handle since the reading is a fast operation.

Types of RFID

Low Frequency RFID uses the frequency band of 30 KHz to 300 KHz, typically in the order of 125 KHz. It's considered to be a short read range RFID, approximately up to 10 cm. Since the distance is so short, the devices are much less sensitive to radio wave interference but due to its low frequency are much slower than other types.

The applications of this type of RFID include access control and livestock tracking.

The High Frequency RFID is set in the frequency band between 3 MHz to 30 MHz. Its range is broader than Low Frequency RFID, from 10 cm to 1 m, which makes it more sensitive to radio wave interference. This type of RFID is most commonly used in ticketing, payment and data transfer.

The Ultra High Frequency (UHF) RFID operates between 300 MHz and 3 GHz band frequency leading to a bigger range than all the other types of RFID frequencies e.g. from 12 m to 100 m. The most commonly used frequency in this type of RFID is approximately 900 MHz, depending on the region.

This type of RFID is the fastest one but also the most susceptible to interference. This is also cheaper and easier to manufacture. Its uses include pharmaceutical anticounterfeiting, retail inventory management and wireless device configuration.

Active RFID systems are characterized by tags with their own transmitter and power source. The transmission of information stored on the microchip is done by broadcasting the tags' signal. Usually, this type of systems work on the UHF Band and its range can go up to 100 m. Active RFID tags can be divided into two categories: transponders and beacons. Transponders are in an idle state until a signal from the reader is received. After that, they wake up and respond to the reader by sending a signal back. On the other hand, beacons send signals at a predetermined interval, depending on the desired level of accuracy. The area being monitored is surrounded by antennas that will read the beacons and get information like location and identification. This last type of RFID tags is used in most real-time locating systems (RTLS).

Passive RFID systems rely on the power transmitted by the reader and the reader's antenna to turn on and send the information back. Since they don't have their own power source, the range that they can achieve is very small, just of few centimeters up to 12 m, maximum. Since passive RFID tags don't require power source or transmitter, this type of RFID is cheaper, smaller and simpler to manufacture than the active one.

For firefighting implementations, RFID systems are being used, or at least tested, but only for fires inside buildings. The details of the RFID applications are explained in a later section.

The idea behind *VitalResponder* is to build a cheap and simple system for firefighters' localization. For a RFID system to work, as mentioned before, there must be a tag and a reader, both placed on firefighters. This would avoid extra work to place antennas in the perimeter of the fire.

The passive RFID would be the best solution considering the situation. But to use Low Frequency RFID tag and reader, the firefighters would need to be very close for it to work properly. High Frequency RFID systems would be the best but the antenna for this type of systems are very large making them impossible for being carried by firemen.

As for active RFID system, in terms of range would be better but would bring two problems. The first one is the fact that they need a battery for reader and a battery for tag, which would make the system to spend more energy than necessary. The second problem is the lack of directionality. The active RFID can detect, for example, 20 meters, but in which direction? Front? Sideways? And within a 20 meters radius, the firemen is 1 meter or 5 meters apart from the reader? The reader only detect that there is a tag within 20 meters but doesn't know how close. And if there is a team of 10 men within that radius, how would it tell which of them is closer?

RFID was a solution put aside in this case because it has a lot of issues that can't be solved under the requirements of the proposed work. There are already some systems that use RFID on the market and they will be presented in a later section.

2.1.5. Laser Range Finder

The principle of operation behind the laser range finder (Figure 4) is similar to the ultrasound. There is an invisible laser beam send by the range finder and, when it hits an object, its reflection is sent back to a chip that will compute the distance of the object. It's extremely fast since the beam is sent at speed of light.

Figure 4: Laser Range Finder [13]

Despite the speed, it is another very expensive solution and according to [14] is not a very good option due to the sensor's erroneous and saturated outputs in low visibility scenarios. It is often set in robots for rescuing operations [15].

2.1.6. Doppler Radar

When talking about Doppler radars, there are two types that need to be distinguished: Doppler radar and Pulse-Doppler radar.

Doppler radar measures the velocity of moving objects and is mostly known by its use by police radars. It sends a beam of electromagnetic radiation waves, at a specific frequency, towards a moving object. The transmitter of the radar sends a wave and its echo is received by that same device. Since the object is moving relatively to the radar, the wave is shifted as outlined by the relativistic Doppler Effect. This way, the frequency of the emitted wave is different from the received one, making it possible to compute the velocity of the moving object.

$$f_{shifted} = f_{original} * \left(\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}} \right) \tag{2}$$

The Pulse-Doppler radar distinguishes from the Doppler radar since it can measure, not only the linear velocity, but also the computation of radial velocities. Due to the sent pulses, this type of radars measures frequency shift and in carrier cycles. The drawback of this system is that there is a maximum speed value above which it can't measure the radial velocity.

Using a Doppler radar in firefighting is not a very common situation due to two main problems arising from this type of radars.

The first problem is the fact that this type of radars measure the velocity of moving objects. One hypothesis is to place the Doppler radar in the firefighter. So even if it is pointing to a wall, the radar will always detect movement because the firefighter is moving. Also if it points to another firefighter and both the firefighters are moving at the same velocity, the detection will indicate no changes in velocity.

The second problem is the size of the antennas. Since they are too big, a new antenna much smaller than the existent ones needed to be developed to be a viable solution.

2.1.7. Tomographic Motion Detector

The idea behind a Tomographic Motion Detector is to surround an area with 28 simple and cheap radio sensors to detect any movement within that area. Since people don't need to carry any electronic device with them, it is much easier and discrete to detect anyone who enters the space.

The radios placed around the area of interest create a dense network of links (Figure 5) since each radio will transmit and receive wireless signals. When someone enters the area, the signal is not going to be reflected back and is possible, by collecting all the signals from all the radios, to sense where the power is being absorbed. All the nodes communicate with each other, transmitting information from one sensor to another to create a mesh network.

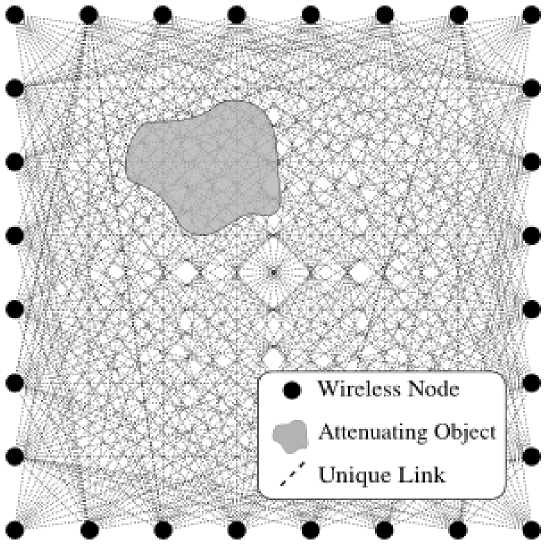


Figure 5: Tomographic Motion Detection [16]

This technology is very effective in people detection but since it is a situation of emergency, the placement of radio sensors around a building becomes an inconvenient. Also, if the building has multiple floors, it is not possible to locate the firemen in the different floors

2.2. Sensor Fusion Systems for firefighting

Firefighters' detection is complicated due to the low visibility conditions, high temperature and the fact that a solution should be usable in different scenarios. When designing this tracking solution, using only one sensor might not be enough. So, one must think about combining different sensors, which provide different information about the movement of the person. In the following subsection, some solutions already existent in the market are described and some technologies under development will be presented to validate the concept of TURF.

2.2.1. Ultrasonic Gloves

Researchers at the University of Minnesota are trying to implement ultrasonic sensors in the firefighters' gloves [17] (Figure 6) to detect walls and people in no visibility conditions. Once the wall and/or people are detected, a vibration signal is sent over to the firefighter. The closest to the object, the strongest is the vibration.

Figure 6: Ultrasonic Gloves [18]

This system was only implemented in laboratory and despite the technology being very simple, the implementation in real world becomes a challenge since it is not practical to add more equipment to the firefighters. They are also studying a way to distinguish people from walls, as a request from the Minneapolis firefighters.

2.2.2. Tactile Helmets

The idea behind the tactile helmets [19] (Figure 7) is similar to the ultrasonic sensors implemented in the gloves of the firemen but this time, a set of ultrasonic sensors is placed on the helmet. When the detection is made, the vibration signal is send to the wearer's forehead through the helmet.

Figure 7: Tactile Helmet [20]

2.2.3. Infrared Camera

The infrared camera (Figure 8) forms images using infrared radiation. The heat sensed by the camera can be precisely measured, allowing the monitoring of thermal performance and heating problems. This is already a solution for firefighting situation but it's a very expensive one and it's not very doable since the firefighters have to carry it on their hands.

Figure 8: Thermal Camera for firefighting use [21]

2.2.4. I-Garment

One system developed by Ydreams is the I-Garment [22] (Figure 9). This system allows the monitoring of the position and vital signals of the firefighter. The collected data is then sent via wireless link to a base station located at one of the fire trucks.

Since I-Garment uses GPS to provide the location, it is not possible to use it in urban fires.

Figure 9: I-Garment System [22]

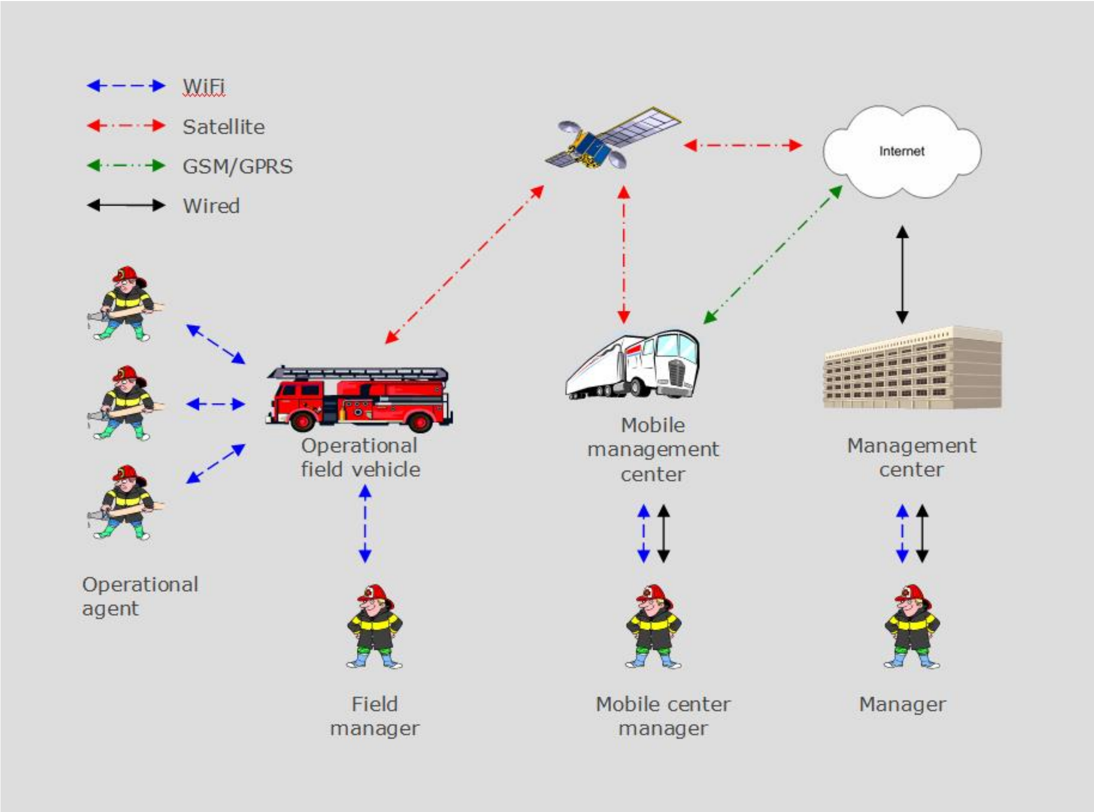


Figure 10: I-Garment Functioning [22]

2.2.5. IMU – Inertial Movement Unit

IMU (Inertial Measurement Unit) [23] (Figure 11) is built using MEMS (MicroElectroMechanical Systems) that allow the coexistence of accelerometers, gyroscopes and magnetometers into small devices. This system is placed inside the firefighter's boots but due to its location is really susceptible to little movements which can lead to errors. Since the actual position is computed based on the last known position, the errors are going to be cumulative which can make the system slightly unreliable.

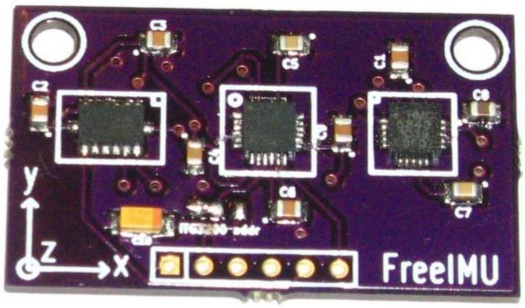


Figure 11: Inertial Movement Unit system [24]

2.2.6. NEON

NEON [25] [26] is a tracking unit developed by TRX Systems. This solution combines information from an IMU, compass, altimeter and ranging sensors that will collect data from firefighters' position allowing the commander to know their exact position. This system also constructs/draws the map of the building in real time.

2.2.7. Q-Track

Another system developed was Q-Track [27], a system that uses an active low RFID tag. Each firemen has a tag in his pocket and a set of RFID readers are placed around the building. Since it's an active RFID system, it can penetrate through walls and is able to know where the firemen are. This system has the disadvantage already mentioned before that firefighters can't spend time placing equipment. Also it can't reach upper floors.

2.2.8. OnSite ERT – Emergency Resource Tracking

OnSite ERT (Emergency Resource Tracking) [28] (Figure 12) is another RFID system for firefighters tracking that is composed by a wearable RFID tag, a lunch-box-sized tag reader and a management console. Once again the idea is to place the several readers around the critical area and since each fireman carries its own tag, the commander can know his firemen position. This is already a commercial system.

Figure 12: OnSite ERT system [28]

2.2.9. GLANSER

The most well-known system, under testing, in this field is GLANSER - Geospatial Location Accountability and Navigation System for Emergency Responders [29] [30] (Figure 13). This is a system for firefighters' localization that does not interfere with their normal activity and does not require any engineer to operate it. As part of this system, there is a microwave radio, a lightweight battery and a set of navigation devices, which include an IMU. By gathering all the information, it will provide to the commander a three-dimensional map of the location of the fireman. It will not provide which floor of the building that man is but will inform the commander if his fireman went up or downstairs using the entrance point as a reference. This system is expected to go to the market at the price of 3000 $, which is almost prohibitive for firemen.

Figure 13: GLANSER implemented on fireman's suit [31]

2.3. The *VitalResponder* Project

The health and well-being of those who care for other people should be a concern of the society. One of the most stressful professions in the world is first responder [32] [33] and many of these men do this job voluntarily. The possibility of managing stress and avoid fatigue in first responders has become a reality and is seen as lifesaving.

The blood pressure provides information about the pressure of the circulating blood on the walls of the vessels. This is one of the main vital signs and can be measured with invasive and non-invasive methods. Invasive methods are used at hospitals and intensive care units and involve catheterization. Non-invasive methods are less accurate but easier to use and portable.

The idea to make this possible is, through non-invasive methods, to measure the blood pressure of a person using wearable technology. In the *VitalResponder*, the two signals combined to measure the blood pressure are electrocardiogram (ECG) and photoplethysmography (PPG). ECG records the electrical activity of the heart while PPG indicates changes in the volume of the blood in a microvascular bed of tissue. The technology used to create the project *VitalResponder* that measures both signals is *VitalJacket*®.

2.3.1. *VitalJacket*®

VitalJacket® (VJ) is the first medical device combining wearable technology with biomedical engineering. It was certified to comply with the “standards ISO9001 and ISO13485 and the cardiology version was approved as a Medical Device for the European market compliant with the MDD directive 42/93/CE, holding the CE1011 mark” [34].

From Figure 14, it’s noticeable the evolution this technology suffered since its prototype to the sports version. The developments and applications of *VitalJacket*® were made by Biodevices S.A, a biomedical engineering spin-off company, using technology originally developed at University of Aveiro.

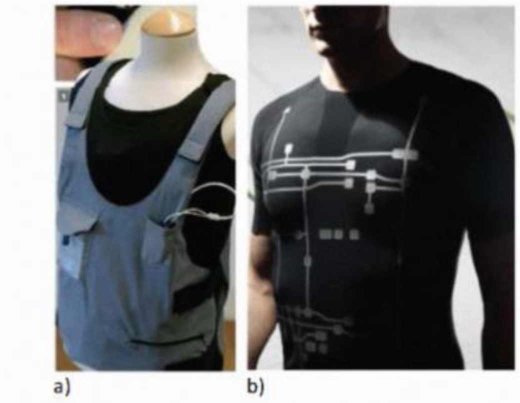


Figure 14: a) VitalJacket® prototype b) VitalJacket® Sports version [34]

The prototype version was composed by a t-shirt with embedded sensors and a jacket for the microelectronic devices (Fig 14 a) while the sports version has all the electronics on the textile of the t-shirt (Fig 14 b).

This wearable technology has two versions for the two goals it can be applied: the sports and cardiology version. The sports version is used in gyms and its user is being continuously monitored, heart rate and ECG signals. All the collected data is send via Bluetooth to the personal trainer and saved to a SD card to be analyzed offline. As for the cardiology version, has 1, 3 or 5 ECG leads and accelerometer and, using not only Bluetooth but also wireless LAN, GPRS or UMTS mobile data networks, allows online monitoring.

Figure 15: VitalJacket® box Digital Recorder [3]

The box shown in Figure 15 records, depending on the user's needs, vital signs as ECG, temperature, movement, posture, actigraphy, respiration, oxygen saturation, etc but also psycho-social variables (panic button, medication delivery, activity habits, location,...). This device is stored in a pocket of the t-shirt.

It's possible, as mentioned above, to communicate via Bluetooth and GPRS Internet connection for online monitoring or save it to a SD card to analize the data offline. The communication of the *VitalJacket®* and data transmission in the *VitalResponder* is performed via Bluetooth with a computer, the *DroidJacket* application for Android or *iVital* for iPhone.

Figure 16: VitalJacket® communication [34]

2.3.2. *DroidJacket*

DroidJacket is an application that allows the data gathering and processing for posterior visualization on an Android device. The data is provided by the *VitalJacket®* boxes that send the ECG (extract the pulse information using Hamilton–Pan Tompkins method [35] and heart beat characteristics to identify arrhythmia problems), physical activity and location information.

The topology of *DroidJacket* is presented in the Figure 17. The boxes from *VitalJacket®* send their information to a VJ Server which is a framework created by Biodevices S.A. that combines the information sent by the VJ boxes (up to four). It provides data to be accessed by external applications. The Mobile Base Station, in this case an Android device, will access the VJ Server to collect the data from the boxes to be processed to the user.

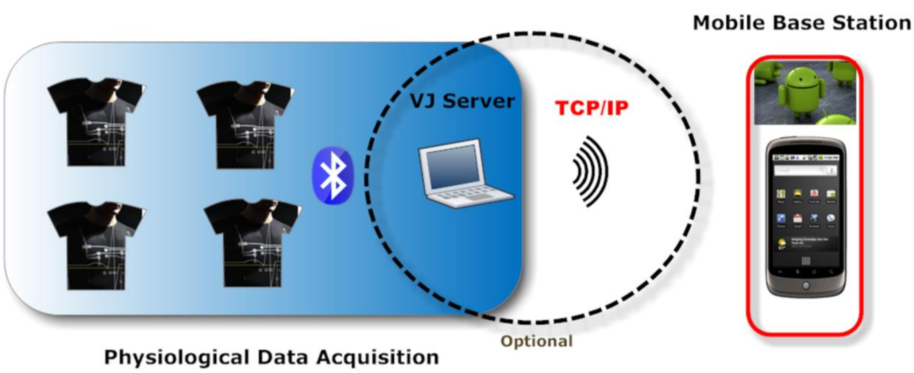


Figure 17: DroidJacket topology [4]

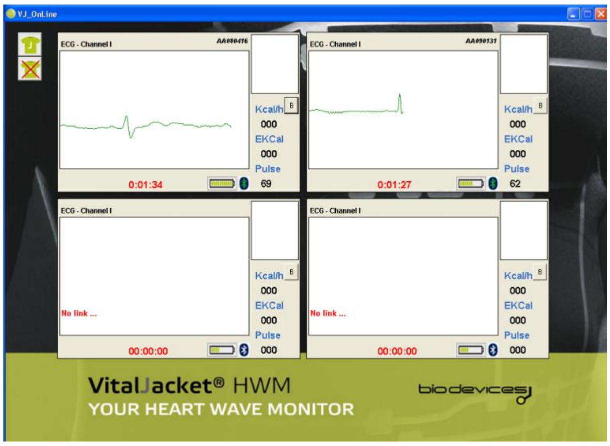


Figure 18: VJ Server [4]

The application itself presents six options to the user: Users, Monitoring, Configurations, Start as Server Mode, Quit DroidJacket and Info (Figure 19). The Users displays a list with username, photo and a jacket icon to indicate the user's state (black, green or red if off, on or alarm, respectively). This tab allows user management so it's possible to update, add or remove users. The Monitoring tab allows the spatial localization of the users, representing each user by its icon. The Info tab shows ECG, pulse, VJ box battery level and personal information.

Figure 19: DroidJacket application screens [4]

2.3.3. iVital

iVital is integrated in the *VitalResponder* project and, similarly to the *DroidJacket*, it uses data collected from the *VitalJacket*® boxes. The main goal of iVital is “to provide a mobile solution to monitor teams of first responders, supporting the role of a team coordinate, with access to the aggregate data” [36].

Figure 20 presents the iVital architecture. *VitalJacket*® has all the sensors embedded in the textiles and this is the mean used to obtain the ECG and location data from all the firefighters. Via Bluetooth, the information is sent to an Android-based smartphone (running *DroidJacket*) responsible for the processing and retransmission of the data ready to be visualized on the iVital Base Station. The communication between the *DroidJacket* and *iVital* is guaranteed via IEEE 802.11 protocol, using TCP/IP sockets.

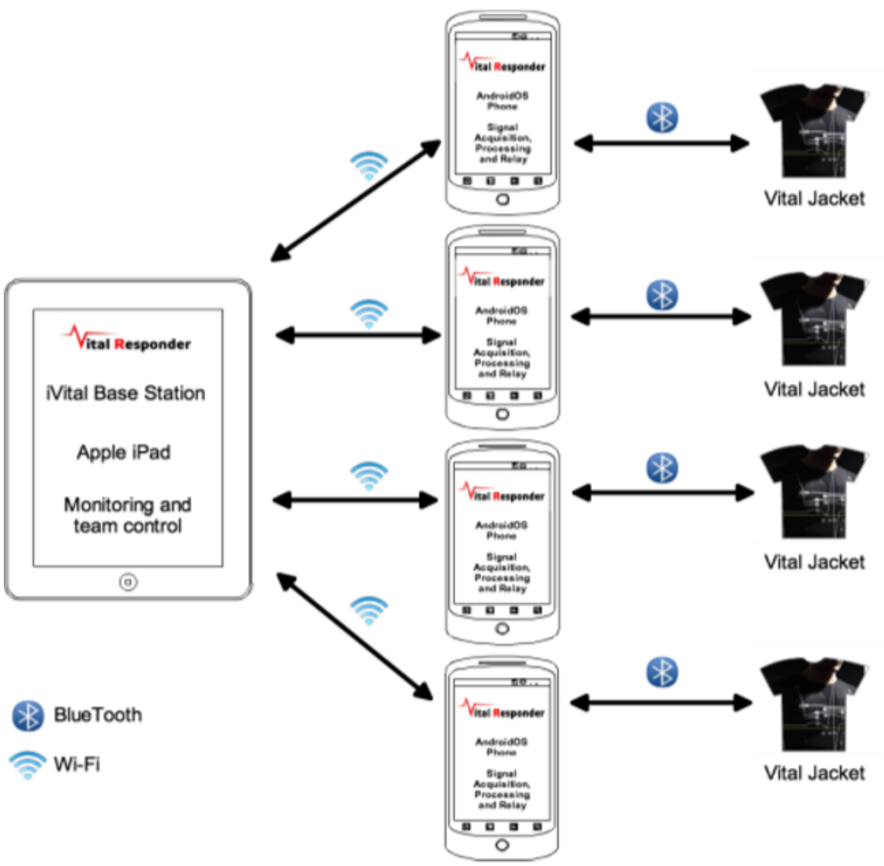


Figure 20: iVital architecture [36]

Each team member carries an Android smartphone running *DroidJacket* application and the data from all smartphones is gathered on the iVital Base Station, an Apple® Ipad in this case. The most important biomedical information displayed in the iVital is the ECG signal that combined with the accelerometers, either from the *DroidJacket* or *VitalJacket*®, provide data and allow the notifications.

iVital is mostly responsible for identifying and displaying the notifications on potentially hazardous situations. These reports are more or less intrusive depending on the severity of the occurrence, such as arrhythmia or loss connection. The following table [36] resumes the classification of the alarms that can be shown on the iPad.

Table 1: Alarm Classification Table [36]

Alarm	Condition	Urgency
Arrhythmia	Classification rules as described [37]	Red
Fall	Classification algorithm based on [38]	Red
Tachycardia	Hearth Rate >= 120	Orange
GPS signal	No GPS signal from User	Orange
Connection	No connection to the DroidJacket	Orange

Similarly to the *DroidJacket* application, it's also possible to have access to the location of all team members through real time mapping. The icon of each firefighter displays, when touched, the info about that man: hearth rate, triggered alarms, graphic ECG tracing, hearth rate graphic history and *VitalJacket*® battery level.

Despite the advantages of the solution, with the Android OS multithreading and the iPad user interfacing, the iVital faced two problems before could be tested on field: the Android doesn't support ad-hoc communications and the iPad doesn't support public Bluetooth API.

Chapter Three

TURF System

TURF stands for **T**racking fireman in **Ur**ban **F**ires and was created to bridge the lack of a tracking system for firefighters when in urban fire situation. Most of the technology available for localization shows ineffectiveness for indoor environments and the rest of it is not enough to solve the problem in question.

A new attempt to solve this problem was developed to complement the *VitalResponder* system. Using an ultrasound and an infrared sensors, it's possible to measure the distance to an obstacle and identify it, respectively. This is an innovative solution since the identification was never tried before as far as the research done for this dissertation was possible.

This chapter is divided in two sections: TURF Hardware and TURF Software.

The first section of this chapter is dedicated to the hardware components of the TURF system and each subsection correspond to a unit of this system. Firstly, the Data Acquisition Unit will present the sensors used, followed by the Data Processing Unit where the choice of the microprocessor is explained. The Voltage Supply Unit addresses the batteries chosen and the voltage regulator used to provide a stable desired tension. Lastly, the Communication Unit subsection gives a description of the Bluetooth module,

The second section refers to the programming and software development for the system. In terms of microprocessor, the programming developed guaranteed the functioning of the sensors, data reading and the communication with Bluetooth via UART. As for Android, an application from *VitalResponder* project was modified to gather the data from Bluetooth, display it on the smartphone screen and save it to the SD card.

3.1. TURF Hardware

3.1.1. Data acquisition Unit

The data acquisition unit is composed by all the sensors that will collect information from the environment. A sensor is a device that reacts according to a physical information, which can be heat, motion, light, etc and converts the information to be read and/or to be processed.

The sensors used in this project are ultrasound, infrared and temperature sensors. The ultrasound sensor reacts to sound waves echo, the infrared sensor is activated with infrared radiation and the temperature sensor output monitors the temperature changes in the environment.

All the data will be digitally converted to be analyzed by the processing unit and to provide the information needed to the user.

Ultrasound Sensor

The principle of functioning of the ultrasound sensor was already explained in section 2.1.1 and the chosen sensor to use in the TURF system is based on that same principle. Recalling it, the ultrasound sensor sends a wave at the velocity of sound and when it hits the obstacle, the echo of the wave is sent back to a receiver. Analyzing the time it took since it was sent until it is received, it's possible to perceive the distance to the obstacle.

Since the sensor will be placed in an environment with high temperatures, this variable must be taken into account when computing the distance. In order to have a more accurate value of the velocity of the sound, the TURF system includes a temperature sensor that will be analyzed in a later section. Adding this variable to calculate the distance, it's possible to use the equation (3)

$$Distance = \frac{c * \sqrt{\theta} * Time}{2} \qquad (3)$$

where θ is the temperature in Kelvin and c is the speed of sound with a value of 340.27 m/s at a temperature of 15ºC and air pressure of 1.2250 Kg/m^3. The used ultrasound sensor chosen was HC-SR04 [39] which is adequate in terms of price, operation principle and availability. Its operating current consumption is 15 mA and when in an idle state it's less than 2 mA. In terms of voltage, 5 V are required for this sensor to work. In terms of angle of detection and, similarly to what was describe earlier, it measures ±15º in the longitudinal plane. The precision can be up to 0.3 cm, until a maximum distance of 4 meters.

The great disadvantage of this sensor is the temperature it can support. Its temperature range goes from 0 ºC up to 60 ºC which might not be enough when considering the temperature at an urban fire can reach 150 ºC, if the sensors are placed in the helmet [40]. In terms of portable alternatives, the maximum temperature range that can be provided goes up to 85ºC, with an increase in weight and voltage supply. An example of an ultrasonic sensor of this type is UB4000-30GM-E5-V15 [41] with a price of 249.78€. To support higher temperatures such as 150ºC, the alternatives are most suitable for industrial applications, making them wired and heavy.

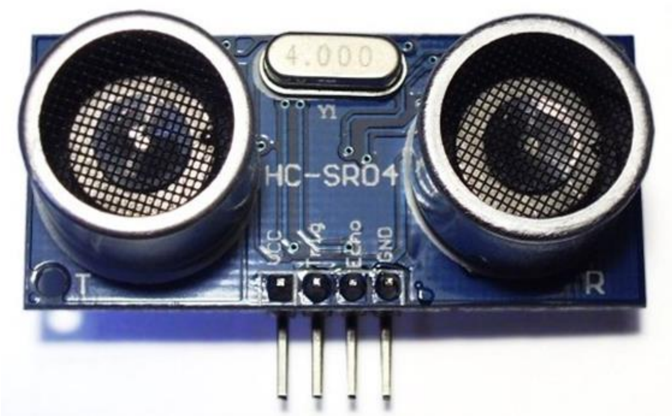


Figure 21: HC-SR04 ultrasound sensor [39]

The HC-SR04 module (Figure 21) has four pins: VCC, TRIG, ECHO and GND. The VCC and GND pins are used for the voltage supply.

For the ultrasound sensor to work properly, a 10 µs signal must to be send to the TRIG pin. It's advisable to wait 60 ms between trigger signals. The electronics of the HC-SR04 will send a 40 KHz signal through the transmitter of the module and the receiver will wait for the echo, which will be presented to the user through the ECHO pin. The time that the signal is at the high level represents the time it took since the signal was sent until the echo was received. The timing diagram of the following figure explains the process.

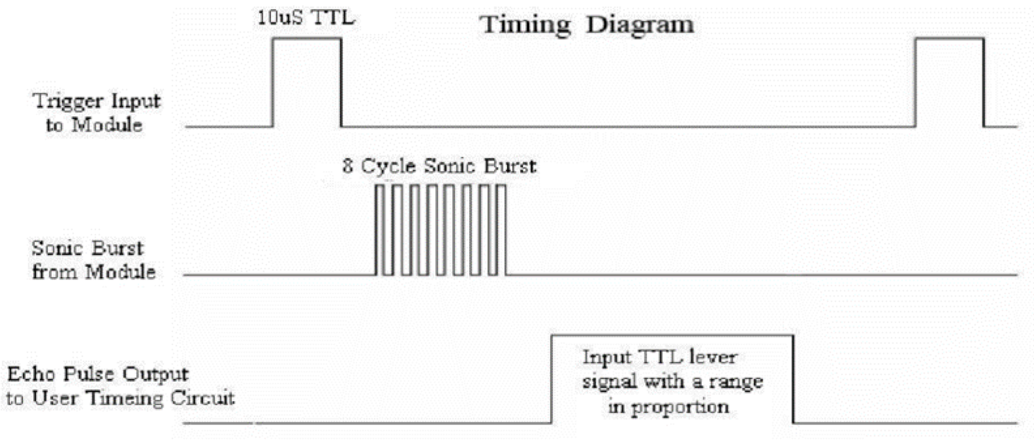


Figure 22: Timing diagram of the ultrasound sensor [39]

Infrared Sensor

The most commonly used infrared sensors are the PIR sensors (Passive Infrared sensor). These are cheap and very easy to find but an alteration was made to use it and take advantage of its good functioning. Instead of having the transmitter and the receiver on the same side, the transmitter is going to be placed facing the receiver but each of them is on a different person. This allows a more accurate identification of the obstacle. If no infrared signal is received, the obstacle is a wall. On the other hand, if the transmitted infrared signal reaches the fireman, then a person is identified.

In order to do this, on the transmitter side, an infrared LED [42] (Figure 23) will be placed with its driving circuit. The chosen infrared LED is SFH486 from OSRAM Opto Semiconductors, because it stands the needed current for the infrared receptor to work. The current consumed is 1 A, in a form of a pulse, and the forward voltage of this LED is 3 V. According to the datasheet of this device, it sends the infrared radiation in a ±11º angle in the longitudinal plane.

Figure 23: SFH486 Infrared LED used in the TURF system [42]

The SFH486 is capable of supporting up to 100 ºC, insufficient if the board was placed in the helmet, similarly to the ultrasound sensor.

As for the polarization circuit needed for the LED to work (Figure 24), a signal is send using the microprocessor and driven through a MOSFET to the infrared LED, as shown in the circuit below.

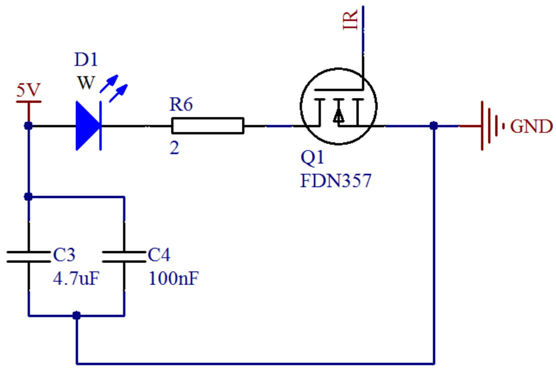


Figure 24: Circuit of infrared transmitter

It requires a high current, 1 A, since the luminosity of the LED is proportional to the current and it only works with a duty-cycle of 10 % at 38 KHz. The signal period is about 0.5 ms and during 1.2 ms there must be silent interval so the signal can be correctly interpreted by the receptor. The timing diagram send to match the demodulation of the infrared receptor is presented in the next figure (Figure 25).

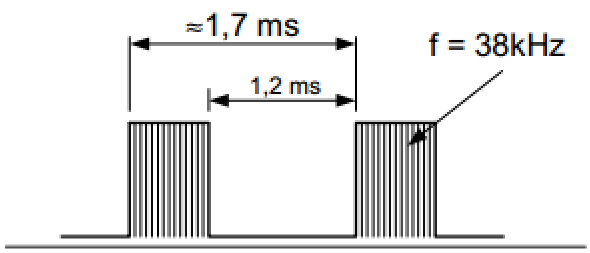


Figure 25: Timing diagram of the infrared sensor [43]

The infrared receptor is TSOP362 [44] (Figure 26) that supports voltage supply from 2.5 V to 5.5 V (chosen 3.3 V) and its low current consumption, 0.35mA, presents itself as an advantage. According to the datasheet, the angle of detection of this device is ±50º in the longitudinal plane. Likewise to the infrared LED, the temperature supported by the infrared receiver is 100ºC.

Figure 26: Infrared Receptor used in the TURF system [45]

It is active low and the implementation circuit of this receptor is very simple as it's observable in Figure 27.

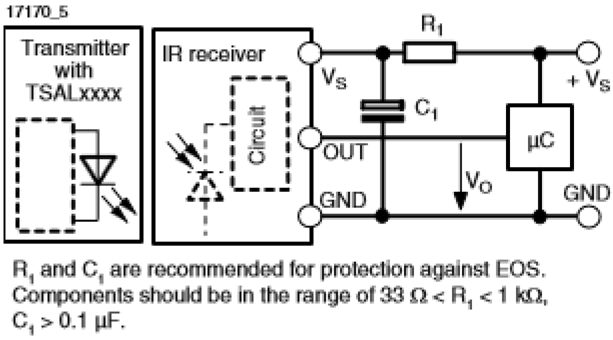


Figure 27: Application circuit for TSOP362 [44]

Temperature Sensor

A correct measurement of the sound velocity requires the knowledge of the ambient temperature. Since it's a fire situation, the temperature is higher than normal so the value of the velocity will change as well.

The chosen temperature sensor is LM335 [46] (Figure 28) which has a low current consumption, between 400 µA and 5 mA. The voltage supply is variable, depending on the resistor R_5 (Figure 28). Similarly to the ultrasound sensor, the temperature supported, or in this case, measured by the sensor goes up to 100 ºC, which might not be appropriate depending on the placement of the sensors, as mentioned above.

Figure 28: Temperature Sensor used in the TURF system [47]

The measurements returned are read by the ADC of the microprocessor, with a precision of 10 mV/ºK. As for the polarization circuit (Figure 29), it only needs a resistor to apply the bias current, 600 µA, to the sensor.

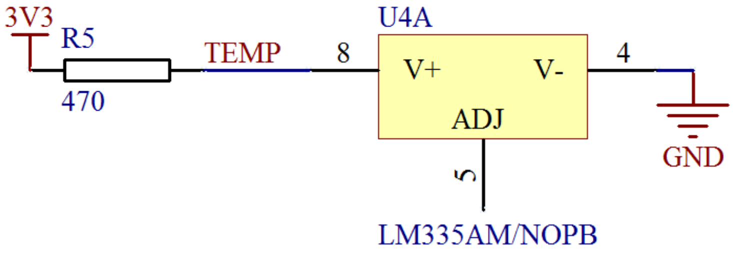


Figure 29: Polarization circuit for LM335

3.1.2. Data Processing Unit

The data processing unit is the central unit of all the systems with sensors whose data need to be gathered, processed and stored. The microprocessor fulfils the functions of a central processing unit in one single integrated circuit. This programmable device accepts digital or analog data, processes it according to stored instructions and provides a digital output to the user.

The output obtained from the microprocessor can be filtered to remove the noise that comes with the signals of the sensors. For the system here presented, there was no need to add filters since the results obtained didn't had noise that affected the final outcome. At the end, data analysis and the information must be as correct as possible.

All data acquired by the sensors is posteriorly sent to the microprocessor for analysis and processing. To choose the right unit, one must think about the capacity of processing, timers, number of pins, etc. For this particular project, the microprocessor must be able to drive 3.3 V, has UART communication protocol, at least two timers and an ADC channel.

After this analysis, the selected microprocessor was PIC24FJ64GA004 [48] from Microchip, which is more powerful than required for this project, but availability in the IEETA Laboratory lead to this choice.

PIC24FJ64GA004 (Figure 30) is available in the 44 pin with TQFP encapsulation which is very practical for this type of projects, where size matters. It has 16 bit resolution, 13 ADC channels with 10 bit resolution, 5 timers and supports interruptions and PWM generation. It works at a maximum frequency of 32 MHz but also has an internal oscillator at 8 MHz and accepts voltage values between 2 V and 5.5 V (for digital pins) with a maximum current of 18 mA.

Figure 30: Microprocessor PIC24FJ64GA004 [49]

3.1.3. Voltage Supply Unit

Since TURF is a portable system, it needs a supply unit to guarantee the energy and the portability of the system. The most common and simple supply units are the batteries due to their small size, low cost, variety and durability.

The most used batteries nowadays for this type of systems are the Li-ion ones where the Lithium ions exchange between the anode and the cathode through liquid electrolyte. In this project, the choice of batteries is Li-Poly, lithium polymer batteries, which do not use liquid electrolyte. Instead, they use a dry electrolyte separator sheet sandwiched between the anode and the cathode, allowing the lithium ion exchange. They are smaller and cheaper than the others solutions, the most important features to be the chosen ones in the TURF system.

Since the battery cannot provide a continuous and constant voltage, the use of voltage regulators is mandatory. These voltage regulators are able to guarantee the voltage value needed, supplying the circuit and avoiding the discharge of the batteries due to the dropout voltage. The voltage regulators do not work unless a minimum dropout voltage is guaranteed.

Battery

The system is supplied by two Zippy single cell batteries (Figure 31), lithium polymer batteries. These batteries are capable of providing 600 mAh 20 C, which mean they grant a maximum current of 12 A. The infrared LED requires 1 A and the 12 A guarantee the functioning of the LED and the rest of the components.

In terms of voltage supply, each battery is capable of providing 3.7 V. Since the ultrasound and the infrared emitter require 5 V and to avoid the use of inductances that cause too much interferences, it's preferable to use two batteries. This way, it's possible to have access to 3.3 V from only one battery and 5 V from the series of the two batteries, after regulating their voltage.

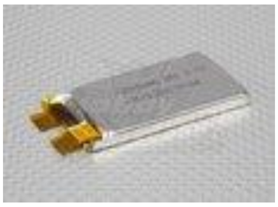


Figure 31: Zippy Battery used on the TURF system

5V Voltage Regulator

Using the two batteries, the total voltage is more than 7 V which means the voltage regulator to be used needs to have at least 2 V dropout voltage. This also guarantees the health of the battery, avoiding it to discharge below 7 V. The chosen one is the L7805 [50] from STMicroelectronics (Figure 32) which guarantees the 5 V output voltage and a current up to 1.5 A, needed for the infrared LED. The D^2PAK is an even better suited package due to its small dimensions.

Figure 32: L7805 used as 5V voltage regulator in the TURF system [51]

From Figure 33, it's perceptible the simplicity of the application circuit, which presents itself as a benefit. The only needed components are two decoupling capacitors to filter the high frequency interferences between the voltage supply and the ground.

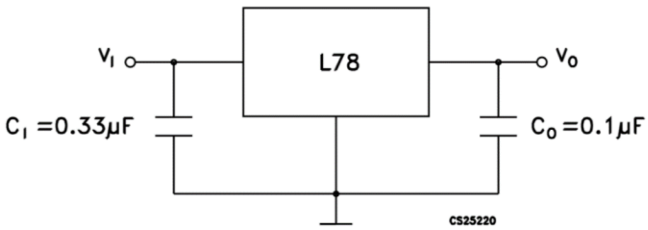


Figure 33: Application Circuit of L7805 [50]

3.3V Voltage Regulator

To provide the constant voltage to the microprocessor and the infrared receptor, a 3.3 V regulator was placed in the circuit, using one of the batteries that are connected in series.

The chosen voltage regulator is MCP1824 [52] from Microchip manufacturer (Figure 34). Its dropout voltage is 0.2 V and since the battery can go up to 3.7 V, this voltage is enough to guarantee the health of the battery. It provides a current of 300 mA which satisfies the condition of the components since the infrared receptor uses 0.35 mA, the microprocessor a maximum of 18 mA, the temperature sensor requires 600 µA and the Bluetooth module needs the most part of the current, 40 mA.

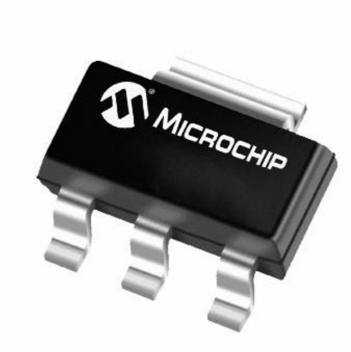


Figure 34: MCP1824 used as 3V3 voltage regulator [53]

As for the application circuit (Figure 35), requires a decoupling capacitor (C_7), a capacitor to stabilize the LDO output (C_8).

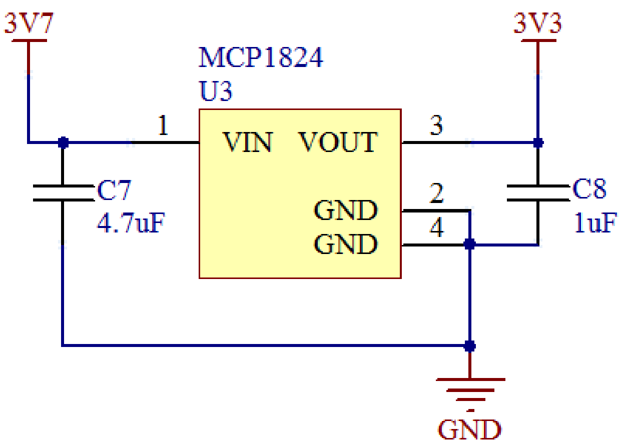


Figure 35: Application Circuit of MCP1824

3.1.4. Communication Unit

After the processing of the data by the microprocessor, it must be send to a device to be interpreted by the end user. To do so, several options can be considered: Wi-Fi, Bluetooth or USB. USB was discarded due to the need of cables which would reduce the portability of the system. Wi-Fi requires extra equipment which cannot be considered for the situation in question.

Bluetooth is the chosen communication mean due to the small size of the modules and the existence of libraries for Android applications, which will make it easy to collect the data sent to the smartphone via UART.

The module is RN-42 [54] (Figure 36) is a Bluetooth 2.0 module chosen due to its existence in the IEETA Laboratory. Its typical supply voltage is 3.3 V and when communicating, the consumption of current is 40 mA, being reduced when it is in an Idle State.

Figure 36: RN-42 Bluetooth Module [55]

The protocol of communication is UART since it only needs to connect the RX and TX lines from the Bluetooth module to the TX and RX lines of the microprocessor. The baudrate used is 56700 bps.

3.1.5. Hardware Project

In order to make the final board of the TURF system, a project was created using *Altium*® software to design the PCB.

The schematics and PCB layout can be found in appendix (Figures 53 and 54). The final result of the product is represented in Figure 37 (Left), before the soldering of the components and in Figure 37 (Right) after the assembly.

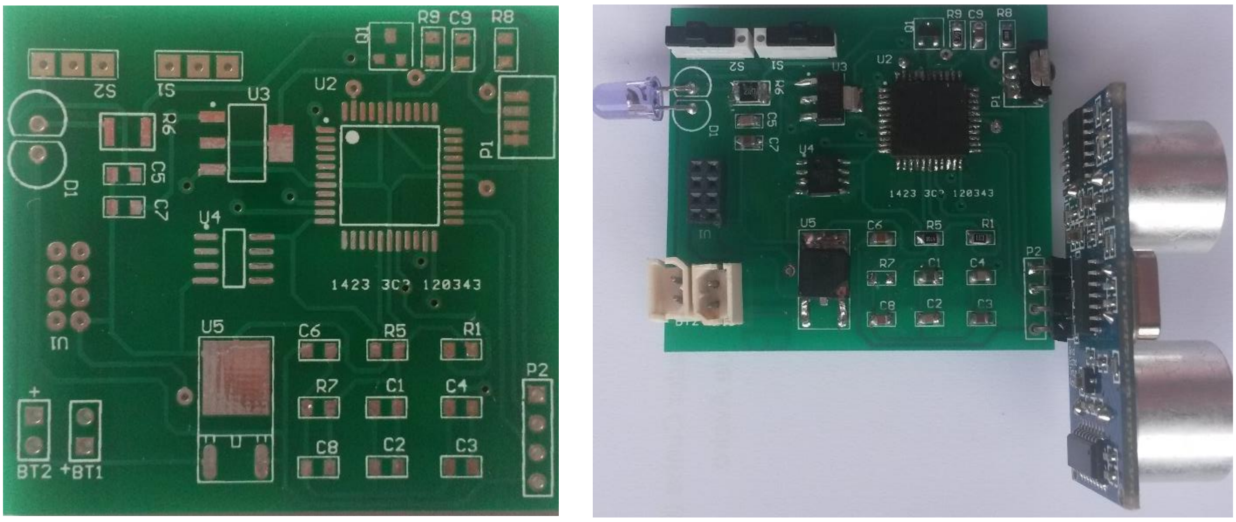


Figure 37: Hardware design (Left) and assembly (Right)

3.2. TURF Software

3.2.1. Microprocessor Software Development

The PIC24FJ64GA004 is responsible for the functioning of the sensors and to do so, it must send the signals already mentioned in the third chapter.

The ultrasound sensor requires a trigger to wake up and the reading of the time of flight in the echo pin. These tasks are performed by the microprocessor for this sensor and this process takes 2.4 ms.

The infrared sensor requires the emission of a signal, coincident with the demodulator of the receiver, and the reading of the receiver pin to analyze the detection scenario. This process requires 12 ms of the microprocessor.

It takes 5.3 ms to complete the printing of the results via UART. The program was designed to have a 500 ms sampling time, to ensure enough time to collect the data, compute and send the results to the UART. The diagram in Figure 38 explains the data flow of the program.

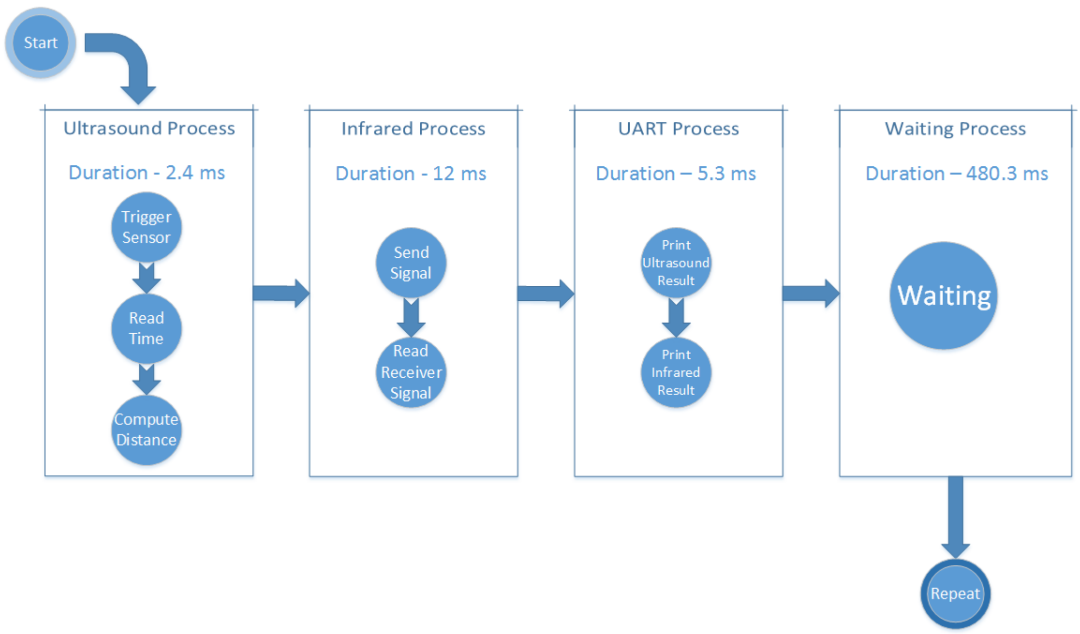


Figure 38: Software Organization Diagram

3.2.2. Mobile Client

The data gathered from the sensors and sent via Bluetooth is going to be displayed in an Android application (app) and stored in the SD card. The *VitalResponder* app is

DroidJacket (see section 2.3.2) and the final goal was to integrate the TURF data with the original project's application but, due to its degree of complexity, it is not easy to merge these two projects. So first, the concept is going to be tested through a smartphone application.

The app developed for the TURF project is the result of an adaptation of a simpler app from the *VitalResponder* project: VRData.

VRData 1.0 is an app that displays and saves to the SD card, for offline analysis, the information about the temperature of two modules placed in different body parts of the firefighter, the carbon monoxide information and the altitude. It allows the discovery and pairing of several devices for receiving the data.

For the VRData 2.0, the one adapted for the TURF system, it has the same data processing procedure, i.e., the app receives the data via Bluetooth, displays it on the screen of the smartphone and saves it to an SD card. More specifically, the information is the distance between firefighters or between a firefighter and an obstacle and also the presence or absence of signal from the other firefighter.

The app discards one sample out of two received from the sensors to improve the processing, displaying and analysis of the samples. Besides it is unnecessary to display samples every half of second.

The navigation menu has two options: exit and connect. The connect menu displays the list of paired devices. The exit option quits the application. This app version only connects to paired devices since it is only dealing with one module, making it unnecessary to discover the different modules. This app was developed for Android 2.2 and last built on the 7th of July of 2014.

The TURF system displays the data in a smartphone Android running, up to the more recent version Android 4.4.2, as mobile client. The smartphone has Bluetooth 4.0 connection and memory card needed for the purpose of the app.

Currently, the only mean for the user to have access to the information is through the screen of the smartphone, which isn't viable/practical in urban fires situations. The integration with DroidJacket would solve this problem since the information is sent to the commander, whom via radio informs his firefighters about the distances or presence situation. Alternatively, a buzzer could be had to the system: the closest the firefighter is from the obstacle, the more noise it would produce.

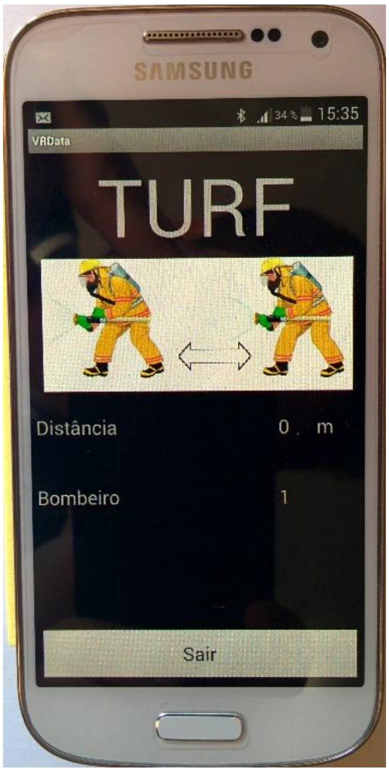


Figure 39: Smartphone used running the TURF application

Chapter Four

Experimental Setup and Results

This fourth chapter is divided in three sections, all related with the experimental part of this project.

The first section is going to introduce the final result of TURF, the setup and the functioning principles that were tested in the field. A financial analysis of the system is also presented since the goal is to build a low cost system.

The second section will describe the tests, including the conditions of testing and the results obtained. This section has three main topics:

- Environmental testing: indoor, outdoor and outdoor with smoke
- Body part placement testing: head, body and leg
- Infrared Sensor testing

Finally, to close this chapter a detailed analysis of the results will be drawn.

4.1. Principle of functioning of TURF

The TURF system is, as explained already, a co-tracking system for firefighters to be used in case of urban fires. The idea is to place one board on the side part of each fireman, where an ultrasound sensor is pointing front to measure the distance ahead of him. Also an infrared receptor reads the information sent by an infrared LED placed pointing back on the fireman in front of him. The scheme in Figure 40 explains the placing of the system and how the data is going to be collected.

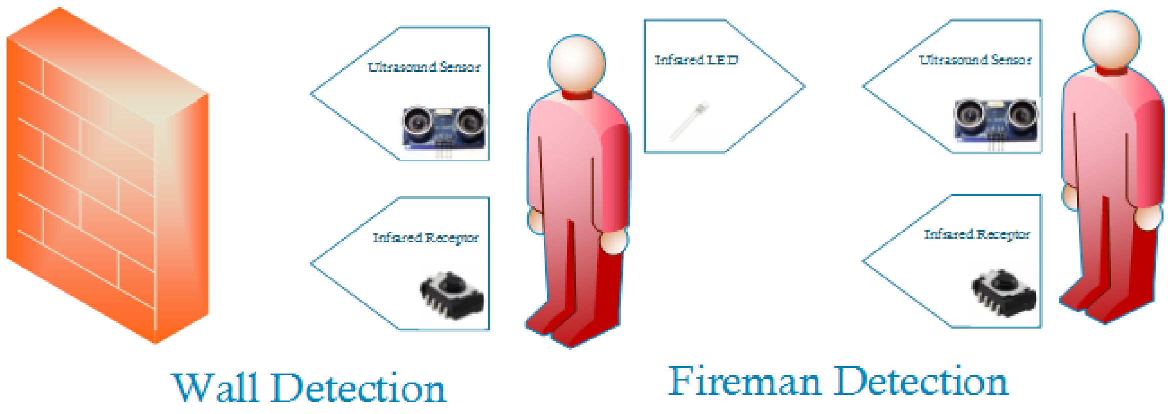


Figure 40: TURF positioning and detection

From Figure 40, it's perceivable the principle of functioning and detection of the TURF system. The ultrasound sensor measures the distance, whether it is from a wall or from another firefighter. This distinction is going to be made by the infrared sensor. If the LED signal is received, then the distance obtained is from a colleague. On the other hand, if the TURF system only receives a distance value and no infrared information, he must be careful about the possibility of be facing an obstacle.

4.2. TURF's Final Product

In Figure 41, it's possible to observe the final result of the TURF system setup. Each of the fireman would have one of these boards placed on their equipment. The test of the best position to put it is going to be analyzed in a later section.

Figure 41: Final Setup of TURF

Since the goal of this project is to design a low cost system, the next table presents the unit cost of the TURF system, excluding the labor and smartphone.

Table 2: Cost of the components of the TURF system

Component	Cost
Ultrasound Sensor	2.31€
Infrared LED	0.27€
Infrared Receptor	1.44€
Temperature Sensor	1.26€
Microprocessor	3.91€
Batteries	8.25€
Voltage Regulators	1.51€
Bluetooth Module	17.39€
PCB Design	1€

These prices are from July 2014 and provide a system with an approximate cost of 38€ in components only. Some of the costs can be reduced, for example by choosing some batteries that provide less current and the Bluetooth module can be changed to a cheaper one, as long as the characteristics remain the same. Most of components described were chosen due to their availability in the laboratory.

4.3. The tests

4.3.1. Testing conditions

In order to obtain results and comparing conditions to make it possible to take valid conclusions of these tests, the TURF system was submitted to four testing scenarios: a narrow aisle (Figure 42 – Left), an entrance hall (Figure 42 – Right), outdoor (Figure 43 – Left) and outdoor with smoke (Figure 43 – Right). The need for the outdoor environment was due to the impossibility of using an indoor space with controlled smoke to properly protect the human testers involved. This way, it's possible to compare the effect of the smoke presence in this environment, since we have the outdoor experiments with and without smoke.

In each of these scenarios, the board was placed in three different body parts: head (simulating the placement in the helmet) (Figure 44 - Left), body (simulating its settlement in the front part of the firefighter's equipment) (Figure 44 – Center) and leg (to test the positioning in the pants) (Figure 44 – Right).

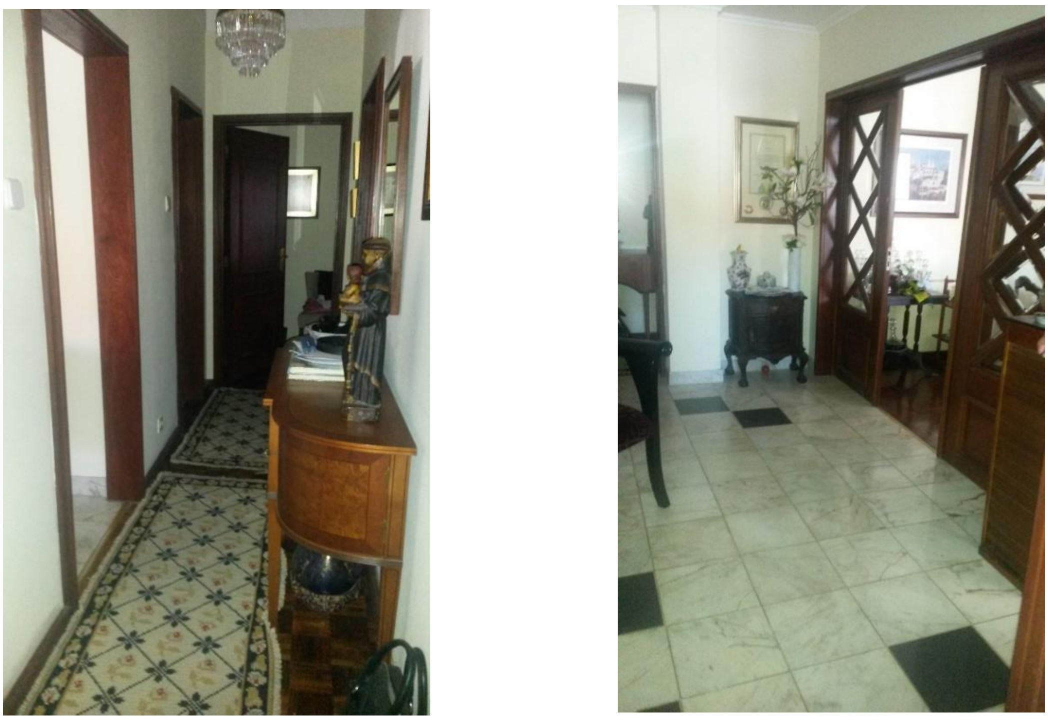


Figure 42: Environment Testing: Narrow Aisle (Left) and Entrance Hall (Right)

Figure 43: Environment Testing: Outdoor (Left) and Outdoor with Smoke (Right)

Figure 44: Testing positions of the TURF system: Head (Left), Body (Center), Leg (Left)

Due to the lack of a final setup with the protection box and the inexistence of training sessions of urban fires in the firefighters' corporations, it wasn't possible to make tests in real firefighting scenario but it was possible to simulate the conditions and perform the tests to have valid and practical conclusion from the results.

The tests consisted in placing one board fixed in one of the body testing points in one of the testers and the other tester is slowly moving away the other board (set in the same point) to see at which points the infrared connection was lost and what was the distance that the ultrasound sensor measures. With the smoke experiments, the source of smoke was put between the two people testing the system.

4.3.2. Test Results by Environment

Four environment testing scenarios were set up to analyze the behavior of the TURF system. These scenarios were indoor (in a hall and in an aisle), outdoor and outdoor with smoke (see Figures 42 and 43). For each experiment, the figures will present three plots with data from the three different placement of the board: Head, Body and Leg (Figure 44). From these tests, a conclusion of the most suitable place to set the board will be taken.

The following pages will present the results obtained. In the different graphics is pointed with a black marker the maximum distance obtained during the tests. Below each graphic is a table to highlight and display the maximum results, in terms of distances and losses by the infrared sensor.

In all the figures, the red line represents the Infrared results, presented in digital values, i.e., one (1) if detected or zero (0) if not detected. The vertical scale in the graphic addresses the ultrasound sensor measurements, represented by the blue line. When the distance is set to 5 meters, it means the ultrasound sensor has lost contact with the reflection targets and can’t measure a close obstacle.

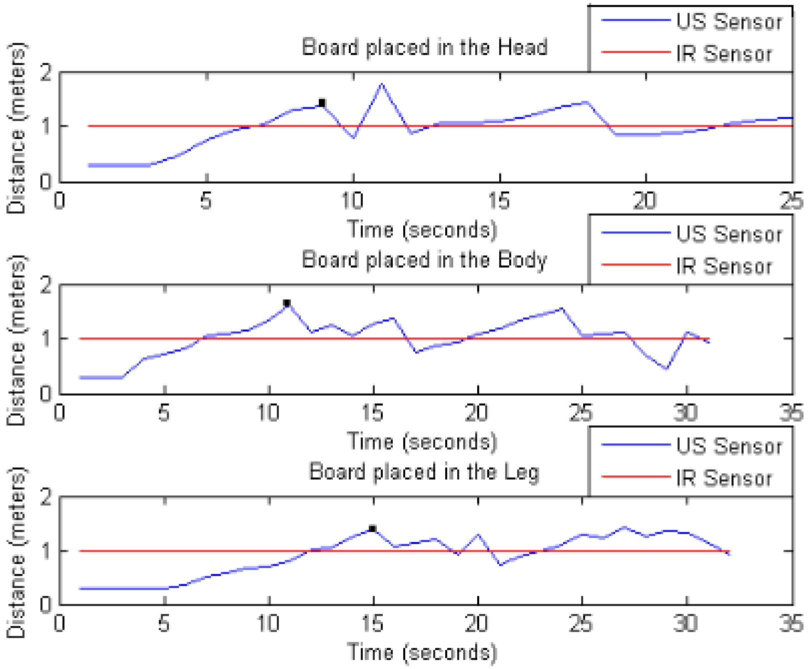


Figure 45: Results obtained in a narrow aisle environment

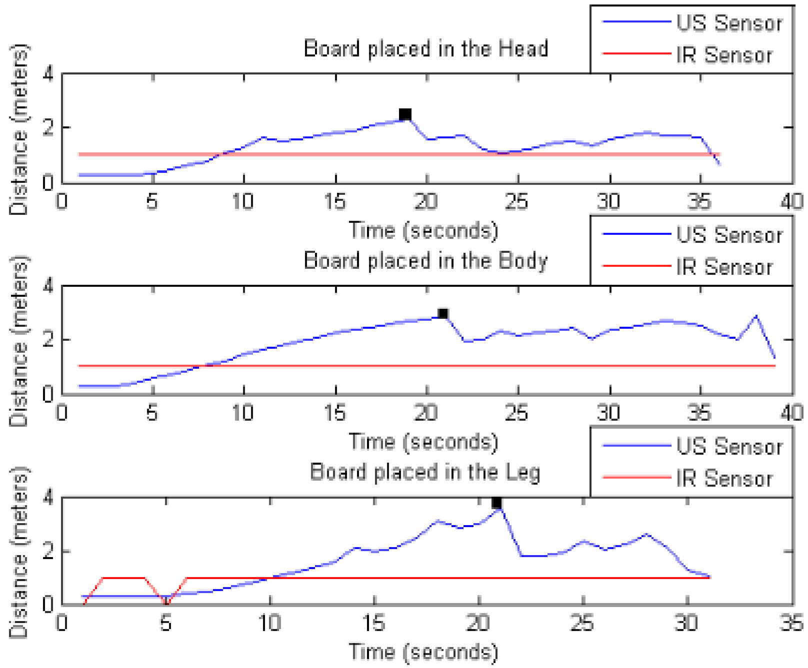


Figure 46: Results obtained in an entrance hall environment

Table 3: Maximum measures obtained for a narrow aisle environment

Body Part	Maximum Distance (m)	Loss By Infrared Sensor (%)
Head	1.37	0
Body	**1.61**	0
Leg	1.41	0

Table 4: Maximum measures obtained for an entrance hall environment

Body Part	Maximum Distance (m)	Loss By Infrared Sensor (%)
Head	2.30	0
Body	2.86	0
Leg	**3.62**	3

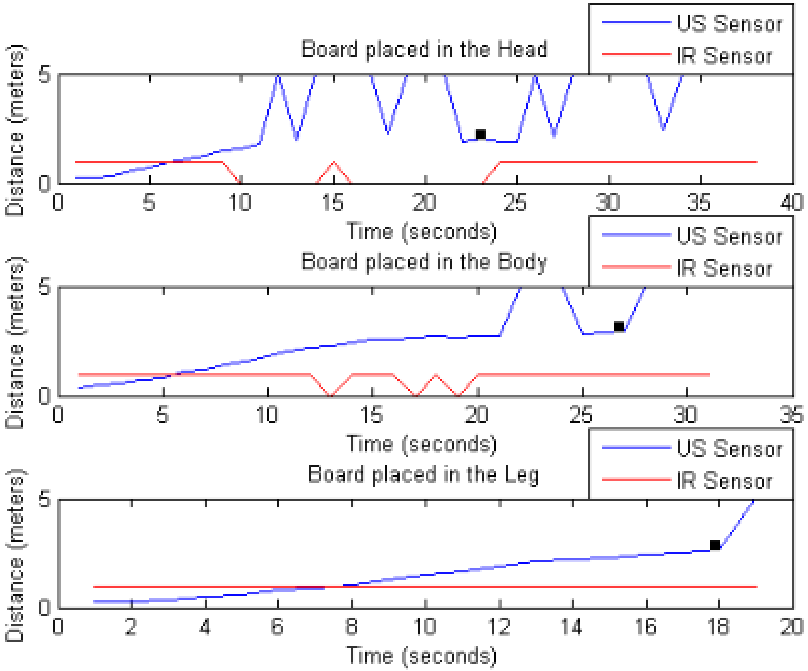


Figure 47: Results obtained in an outdoor environment

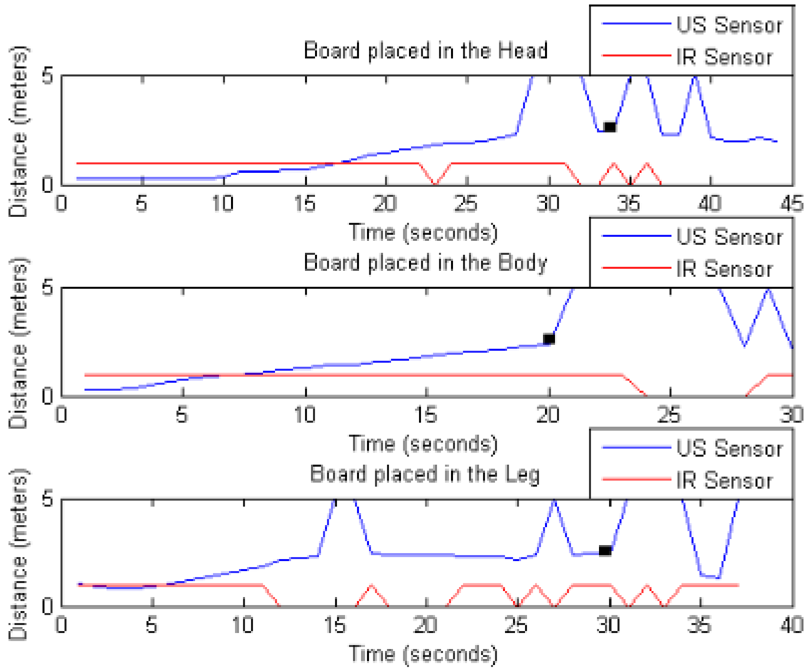


Figure 48: Results obtained in an outdoor with smoke environment

Table 5: Maximum measures obtained for an outdoor environment

Body Part	Maximum Distance (m)	Loss By Infrared Sensor (%)
Head	2.00	29
Body	**2.96**	10
Leg	2.67	0

Table 6: Maximum measures obtained for an outdoor with smoke environment

Body Part	Maximum Distance (m)	Loss By Infrared Sensor (%)
Head	2.44	25
Body	2.32	13
Leg	**2.47**	30

There are some points that are important to justify the discrepancies obtained in the experiments.

The first test was performed in a four meters aisle (Figure 45 and Table 3) and it points out a very predictable situation: the ultrasound sensor stops measuring the person in front of the sensor and starts showing a distance to a wall, as the result of the reflections the ultrasonic waves suffer. This distances aren't as high as the ones seen in the other situations but it's an aisle and considering more than a man there, they won't be apart for more than 1 meter.

The second set of results presented (Figure 46 and Table 4), the detection range is wider due to the lack of walls in contrast with the narrow aisle, with a difference of approximately 2 meters when comparing the best locations in both cases. Similarly to the aisle situation, the infrared sensor never stops detecting due to the angle of detection and range (analyzed in section 4.3.4).

Moving now to the analysis of the outdoor situations the results displayed different response than the ones obtained indoor. The differences in the infrared sensor data can be explained by the movement of the body. With smoke, and since the people testing the system weren't using any means to protect the respiratory tract, natural defense movements against more intense smoke were made, making the infrared detection instable. As for the values obtained by the ultrasound sensor, it is evident a decrease in the maximum distance since it was a windy day and the ultrasonic waves are reflected by it, since the wind creates an invisible barrier.

4.3.3. Test Results by Body Part

The test of the body parts placement allows the drawn of very important conclusions regarding the following question: how will the specific location behave in the different scenarios?

The three tested parts were head, body and leg (see Figure 44). For each of the figures representative of one positioning, three graphics are displayed: the first one represents the indoor environment, the second shows the results for the outdoor space and the outdoor with smoke measurements are shown in the last graphic.

Similarly to the previously presented graphics, the marked points represent the maximum distances measured in each of the experiments. The organization of the results page is the same as the ones shown before: a graphic for each body part and a table below to expose the maximum distance value and the losses by the infrared sensor.

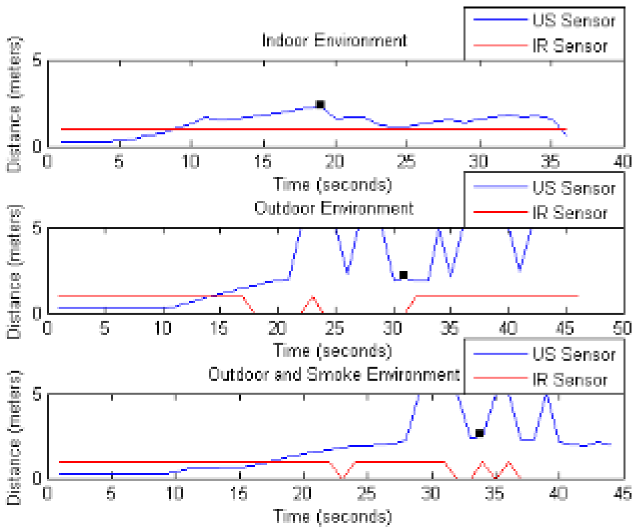


Figure 49: Results obtained for the head placement

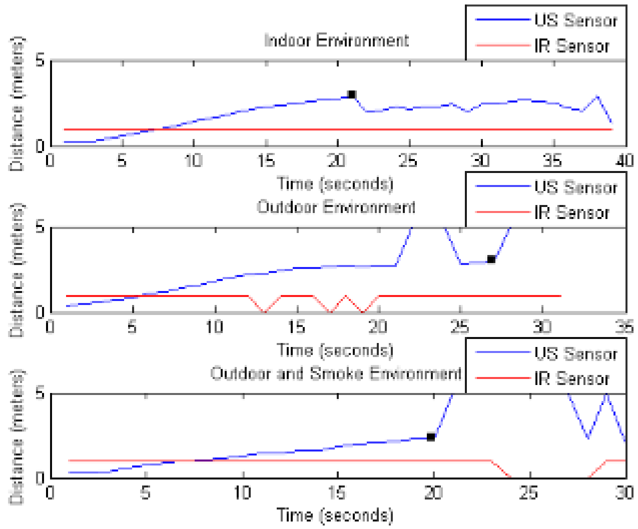


Figure 50: Results obtained for the body placement

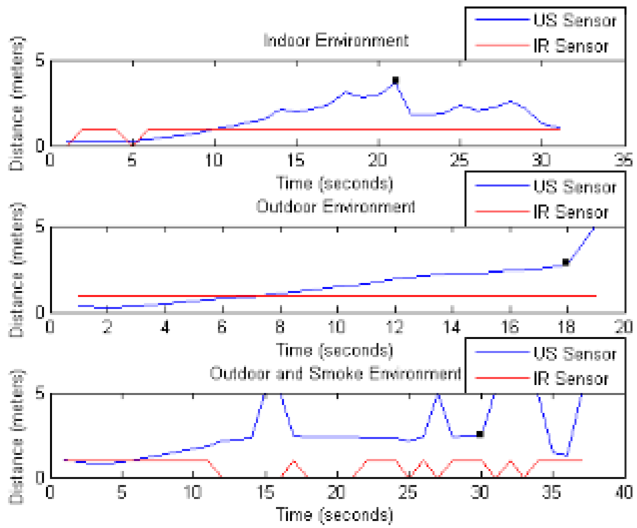


Figure 51: Results obtained for the leg placement

Table 7: Maximum measures obtained for the head placement

Environment	Maximum Distance (m)	Loss By Infrared Sensor (%)
Indoor	2.30	0
Outdoor	2.00	29
Outdoor with Smoke	2.44	25

Table 8: Maximum measures obtained for the body placement

Environment	Maximum Distance (m)	Loss By Infrared Sensor (%)
Indoor	2.86	0
Outdoor	2.96	10
Outdoor with Smoke	2.32	13

Table 9: Maximum measures obtained for the leg placement

Environment	Maximum Distance (m)	Loss By Infrared Sensor (%)
Indoor	3.62	3
Outdoor	2.70	0
Outdoor with Smoke	2.47	30

Some values presented above are not consistence with what would be expectable. Some explanations will be now presented to clarify these inconsistences.

The head placement scenario is only one where the distance increases with the presence of smoke. This can happen due to the natural movements of the head. Since it is the part of the body that moves the most, it is difficult to maintain the head of the two testers aligned all the time, making the ultrasound sensor to lose contact with the individual in front of him.

As for the outdoor distances (Table 8) when the board was placed in the body, the verified difference is explained by the reflections suffered by the ultrasonic waves when the smoke was introduced. The loss of contact on the infrared sensor is the result of the movement of the body as explained before.

In the leg positioning, the overall infrared detection is good, with exception for the smoky situation (Figure 51, last graphic) but, as mentioned before, the testers weren't using any protection for the respiratory tract making it difficult to keep the board pointing front.

4.3.4. Test Results of the Infrared Sensor

The infrared sensor behaved differently in all the experiments, making it necessary to perform extra tests to realize if the results presented were caused by environmental or human reasons.

The first test consisted in placing a source of fire between the emitter and the receiver of the sensor. The response obtained from the device was positive, making the detection all the time for all the distances. This test make it possible to conclude that the missed detection moments were not related with the environmental conditions but due to the board oscillation with the motion of the body.

With a careful observation of the results can be seen that even these losses are not very significant because the system reconnects in few seconds (less than 5 seconds) and this event doesn't occurs frequently. To address this problem, a simple filtering process can be applied. Since the measures are being taken every second, a filter could be used to only consider a detection/not detection event after, per example, 3 consecutive positive/false samples which would improve the performance. This would also become an advantage since it would avoid the false alarms presented, for example, when a firefighter turns a corner. The following graphic (Figure 52) will show the results obtained when implementing the filter to the outdoor with smoke environment, considering 3 samples to make the decision of detection/non detection. Table 10 show the comparison of losses by infrared sensor before and after the filtering process.

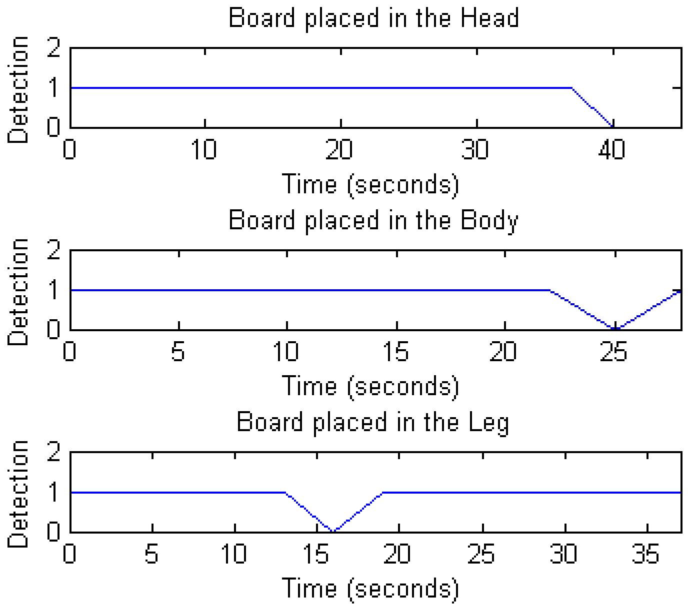


Figure 52: Results obtained for outdoor with smoke environment after the filtering process

Table 10: Comparison of the losses of the infrared sensor before and after the filtering process

Body Part	Loss Before Filter (%)	Loss After Filter (%)
Head	25	14
Body	13	10
Leg	30	8

Other possible options is to improve the inherent system performance by change to a better, more sensitive infrared sensor or add an extra receiver in the board to increase the system range.

The second test was elaborated to understand the angle of detection of the sensor. According to the datasheet, the infrared receptor TSOP362 has a half detection angle of ±50º and the infrared emitter's (SFH 486) half detection angle is ±11º. The practical tests revealed a detection angle of ±60º in the longitudinal plane and on the transversal plane, the detection occurred in all the angles. This results make it noticeable that there is a need to find a narrowing protection to the infrared receptor so the detection is only made in the same angle of detection as the infrared emitter in the longitudinal plane.

4.4. Results analysis

The analysis of the results shown above will be done through a comparative table of the results obtained for the different environments and for the different body parts.

Table 11: Comparative Table of the results

Environment	Maximum Distance (m)			Loss By Infrared Sensor (%)		
	Head	Body	Leg	Head	Body	Leg
Indoor (Entrance Hall)	2.30	2.86	**3.62**	0	0	3
Indoor (Narrow Aisle)	1.37	**1.61**	1.41	0	0	0
Outdoor	2.00	**2.96**	2.70	29	10	**0**
Outdoor with Smoke	2.44	2.32	**2.47**	25	**13**	30

Starting with the indoor environment, the system performed better when tested in a hall entrance than an aisle. Naturally, the reflections on the walls and angle of detection of the sensor make it difficult to keep measuring the distance in a straight line.

When in the narrow aisle, the maximum distance measured was 1.61 meters with the board besides the chest. As for the hall entrance, the distance was more than double, reaching the value of 3.62 meters with the board on the leg. The infrared sensor kept the detection all the time, with an exception for the leg positioning that missed the detection with a percentage of 3 %.

The outdoor environment was required to test the response of the system with smoke presence, due to the fact that wasn't possible to evaluate the smoke situation in an indoor scenario. The best performance obtained in terms of distance was 2.96 meters, when the board was placed on the body. In contrast, the best results for the infrared sensor occurred when placing the sensor on the leg, having a constant detection of the presence of the person. Confronting this result, the less suitable place to put the sensor is the head with 29 % chance of missing the detection.

Analyzing now the smoky environment, the placement of the board on the side part of the leg presented itself as the best solution in terms of ultrasound measurement, obtaining a distance of 2.47 meters. As for the infrared sensor, the best location seems to be the body with a missing percentage of 13 % against the 30 % of missing when placed on the leg. A filtering process would improve the percentage of missed detections.

Chapter Five

Conclusions and Future Work

This chapter will present the main conclusions of this project, among them:

- The viability of this project;
- The best placement for the TURF' system and the reasons for the choice ;
- The temperature analysis and the resistance of the system to these temperatures.

The testimony of Francisco Santos, commander of the corporation of volunteer firefighters from Águeda, is presented to explain the advantages and disadvantages of the proof of concept of TURF from a real firefighting situation point of view.

To end this dissertation and since this is a work under development, the most important aspects that need to be improved are going to be described.

5.1. Conclusions

After analyzing all the results and summing up the information, this is a system with conditions to be implemented and that could, in fact, help firefighters in specific situations as urban fires.

The results were studied by body part and by environment but to make it possible to perceive what the best place is to integrate the TURF' system in a wearable device, a merge of the conclusions taken from both tests must be made.

The infrared sensor performed well, without losing contact when tested in the smoke environment. This allows to conclude that the connection isn't lost due to environmental causes but because of the movements of the body. A filtering process would improve the detection method and avoid false alarms.

The two most important tested environments are the indoor and smoke environment, since the urban fire scenario is similar to the conjunction of these two scenes. So, the placement on the leg would be the best since it performed better in these two scenarios. The body was the best place when in the narrow aisle but there is a factor of location that must be taken into account.

In some situations, firefighters must crouch and if the placement is done on the body, the ultrasound sensor would be facing down measuring only the distance to the floor which is not a relevant measure. There is always the possibility of the arms interfere with the measurement when the system is placed on the leg but one must consider that the arms are aligned with the legs when crouching and the system is slightly outside this line of sight. The interferences will happen but won't be significant since the system takes one value per second.

Another conclusion that is important to mention here, is the temperature reached in the firefighters suit to understand if the system would support the high temperatures of the fire. The placement chosen based on the tests of the performance was the thigh. In this area, the temperature reached outside the cover of the firefighter is 61ºC [40] which would be supportable by the components of the system. The ultrasound sensor would be the one facing more difficulties since its maximum temperature is 60ºC.

5.2. Future work

To understand the pros and cons of the proof of concept of TURF, it is important to know the opinion of the people who deal with firefighting every day and know the real conditions of an urban fire.

Francisco Santos is the commander of the corporation of volunteer firefighters from Águeda and was very helpful in the evaluation of the work done so far. He definitely thinks this could be an extremely useful product, specially the detection of obstacles characteristic. According to him, when they enter a building, they use mostly the hands to orientate themselves since there they don't have any equipment to help them to do that.

The aspects that he pointed out as being disadvantageous were:

1. The use of the smartphone: there should be a way for them to know the values (currently displayed on the screen) without taking the smartphone inside the burning building. They can't take the gloves or take the smartphone off the pocket, since both their hands and smartphone would melt. He added that the smartphone should never enter the building, even if it only works as a mean to send the data to the chief of operations outside the building.
2. The absence of a noise signal: since firefighters can't see the screen of the smartphone, it would be important for them to know how close they are from an obstacle. A noise signal would play with increased frequency as the distance became smaller.
3. The infrared sensor could have false alarms: when the man in front turns the corners or climb stairs, the sensor would give a false negative.

As this is a project under development, the TURF system would need some improvements to make it wearable and make it a product. The suggestions of the commander of Águeda were also taken into account when thinking about the changes that could be done.

To start with, it would need a functional setup to hold the boards and the batteries together. This setup could also include components with smaller packages to make the PCBs smaller. The protection box could be made of a fire resistant material to protect the components from high temperatures. Only this way, it would be possible to make it to test in a real life firefighting scenario.

The second change it would need is a way to measure the battery level and send the information to the commander. This could be done with a resistor divisor and ADC reading. Also, the batteries would need an integrated USB charger to make it possible to charge them easily. The addition of MAXIM 1555 [56] would make it possible to connect the board directly to a computer or some other device that could provide energy via USB.

The addition of a buzzer would be a very important change, according to the firefighters. It would allow them to have a sense of their bearings and not use their hands so much to locate themselves.

One of the most important developments in terms of future work would be the full integration of the TURF data with the *DroidJacket* and the *VitalResponder* wearable technology. Due to the complexity of the project, it was not possible to make this incorporation for the moment of this dissertation but it would be very important to allow the monitoring of all the members of the firefighting team (since each of them would carry a smartphone connected to the command) and system characteristics, as battery level, for example. This could also solve the problem pointed out by the firefighters' commander from Águeda since the men wouldn't need to look at their smartphones, if the smartphone could support the urban fires temperatures.

Another way of solving the first disadvantage point out by the commander is to use a Wi-Fi or mobile data module instead of a Bluetooth module. This way, the data would be send directly to the commander outside the building, making it unnecessary to use a smartphone.

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Appendix A – TURF schematics

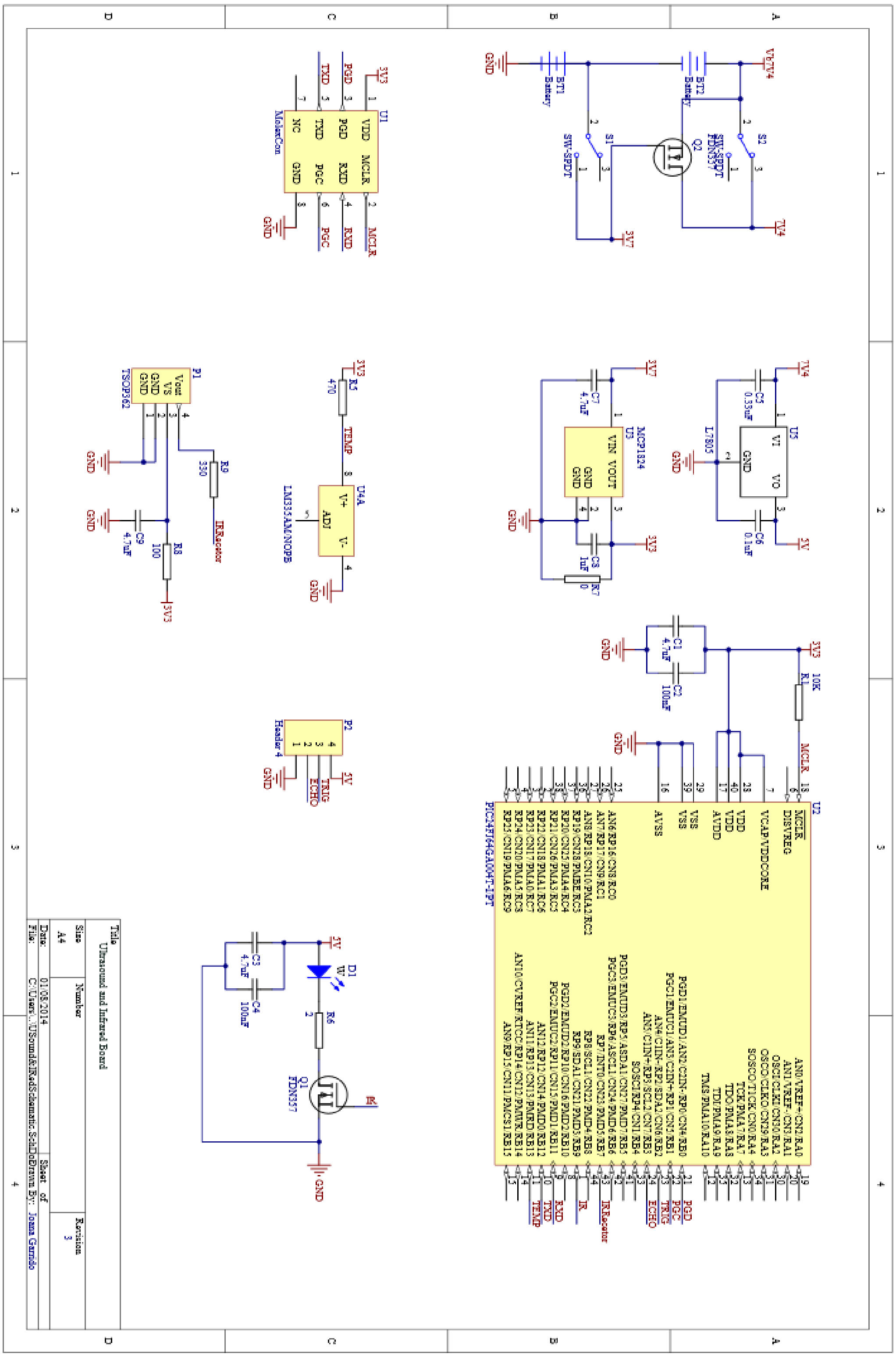

Figure 53: TURF schematics from Altium®

Appendix B – TURF PCB Layout

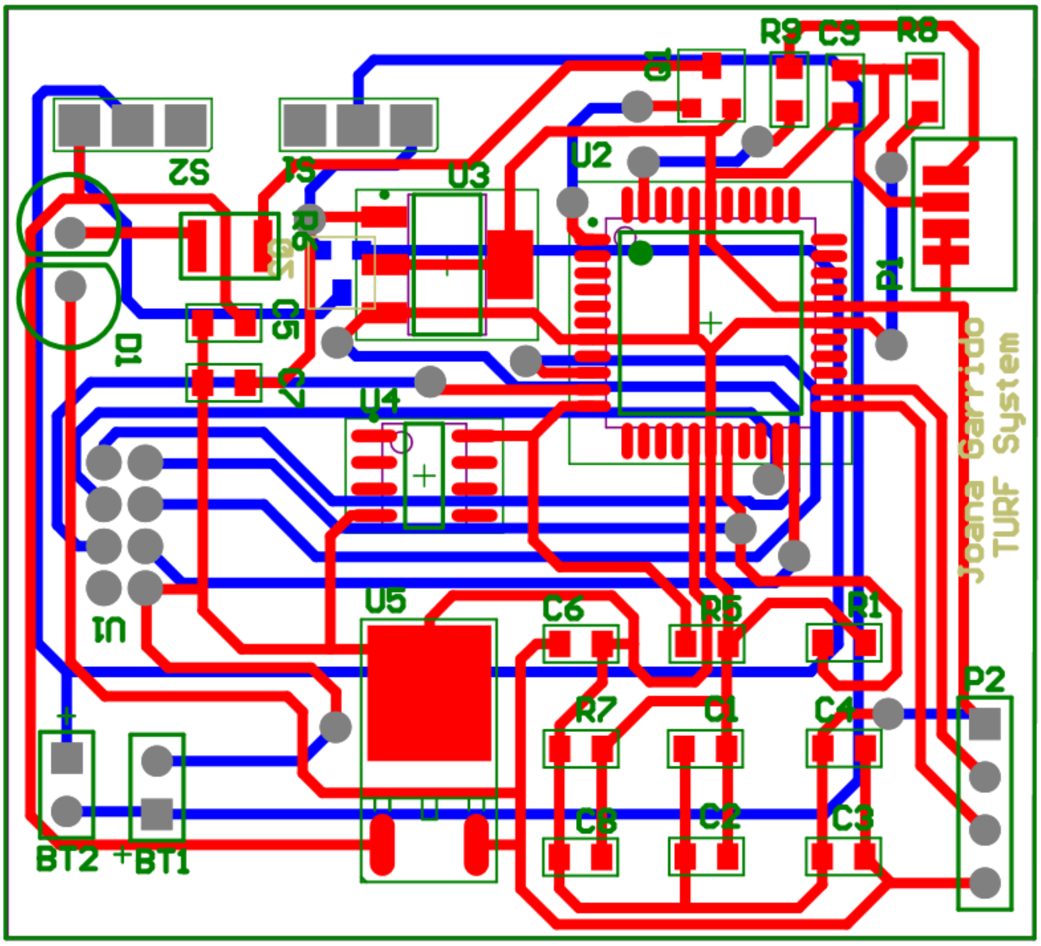

Figure 54: TURF PCB Layout from Altium®