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VitalHelmet – Towards a sensorized helmet for First Responders

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Resumo

A presente dissertação está inserida no projeto *Vital Responder* e tem como principal objetivo desenvolver e integrar um sistema autónomo para ser usado por bombeiros e capaz de medir a concentração de matérias perigosas e gases presentes num cenário de emergência.

Seguindo a linha de investigação do VR na área de equipamentos vestíveis , ir-se-á desenvolver um módulo para o capacete capaz de ser adaptável a vários cenários desde incêndios florestais a incêndios urbanos e industriais, como indústria química, refinarias de petróleo, indústrias de plástico, etc. Espera-se que a solução aqui proposta venha a ser capaz de salvar vidas e, ao mesmo tempo, proteger a saúde dos agentes de primeira linha - não importando qual seja a missão. Desta forma, propomos uma inovação no que diz respeito à medição de gases e proteção da saúde dos bombeiros.

Tanto quanto temos conhecimento, esta abordagem é inovadora uma vez que não há equipamentos capazes de se adaptarem a diversos cenários. Para além disso, a presente proposta é uma solução leve e de custo reduzido, comparativamente com os restantes detetores de gases.

Para conseguir a criação de tal sistema, desenvolveu-se o *Vital Helmet*, uma caixa a ser colocada no capacete dos bombeiros que medirá variáveis ambientais tais como luminosidade, humidade, temperatura, altitude e pressão atmosférica. Terá também GPS e uma câmara.

O sistema é maioritariamente composto por um sensor, um circuito potenciostático, um ADC externo (opcional) e um microcontrolador. O ADC externo é facultativo uma vez que o sistema continua a operar corretamente sem este. Contudo, a precisão do mesmo será inferior.

Esta dissertação introduz o design do harware bem como apresenta pseudo-código. Ao abrigo da mesma, dois sistemas de hardware foram desenhados, projetados e soldádos. Nesta tese, a performance da solução é avaliada através de testes experimentais. Contudo, como até à data não foi possível proceder à calibração dos sensores, não se poderam tirar conclusões mais detalhadas.

Os resultados levam à possibilidade de adaptar o sistema para outros cenários para além do mundo dos bombeiros, como minas ou esquadras policias.

Resumidamente, é apresentado um equipamento destinado a proteger o usuário dos riscos representados pela presença de gases contaminantes num cenário de emergência.

Abstract

The present proposal lies within the framework of the *Vital Responder* (VR) project, and its main goal is to develop an autonomous device —to be used mainly by firefighters— to measure the present concentration of hazardous gases. This information will then be compared with the norms established by the safety regulatory entities for work medicine.

Following the development of the VR wearable platform, the present project aims to evolve the Helmet Unit's hardware sensing architecture so that it can have different sets of environmental sensors adaptable to different critical scenarios such as chemical industry, petrol refineries, forest fires, urban household fires, etc. It is expected that the proposed solution will be able to save lives and at the same time protect first responders' health —no matter what the mission is. Thus, we propose a major novelty on the gas monitoring and in firefighters healthcare.

As far we know, this approach is innovative since there are no devices capable of being adaptable to various sensors. Furthermore, the prototype presented is low weight and has a considerable reduction in the cost when comparing with other portable gas detectors.

In order to reach this solution, we developed the *Vital Helmet*, a box to be held on the firefighter helmet and that measures luminosity, humidity, temperature, altitude and atmospheric levels and has GPS and camera.

This system is mainly composed of a sensor, a potentiostat circuit, an external ADC (optional) and a microcontroller. An external ADC is facultative since the system keeps working correctly without it but with a lower resolution.

This thesis introduces the hardware module design and presented some pseudo-code used. Under this dissertation two hardware projects were designed, implemented and soldered. It also evaluates its performance by means of experimental analysis. The results of these tests prove that the system behaves as expected. For extra certainty of performance and operation a calibration is necessary.

The results of this dissertation bring up the potential to adapt our system to other scenarios beyond the firefighter brigades, such as mines and police brigades.

Briefly, it is presented a device to protect the user of the risks posed by the presence of pollutant gases by emergency scenario.

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First of all, I woud like to thank my supervisor, Professor João Paulo Cunha for giving me the opportunity of joining this challenging project as well as all my colleagues who belong to this team for helping me with everything I needed. I would like to give a special thank to my two lab mates Mário Espinoza and Pedro Costa. The former for all the brainstorming we had and to the later for all his friendship and comprehensiveness.

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To Professor Pedro Guedes de Oliveira who was and will always be an example as a professional and human being. I claim that he was the best teacher I ever had. A dedicated teacher not only in teaching but also worried about his students well-being. To him, I will always be grateful.

To my parents who always supported me providing all conditions to conquer my dreams doing everything they could do.

To my grandfather who taught me how important in life is to be a good professional, loyal and hard-working.

And finally but not less important:

To all the firemen and specially to you, eternal partner and friend Fernando Reis (3rd category, fireman number 45) and other partners lost in fire during the fateful Summer of 2013, my sincere thanks for all the knowledge, example of courage and motivation that you conveyed and still convey. To my fire department corporation from Valença for having been my family many times and my first house.

Susana Ribeiro D'Eça

"Imagination means nothing without doing."

Charlie Chaplin

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Acronyms

ABS	Acrylonitrile Butadiene Styrene
ACK	Acknowledge Condition
A/D or ADC	Analog-to-Digital Convrter
ANPC	National Authority for Civil Protection
BLEVE	Boiling Liquid Expanding Vapor Explosion
CE	Counter Electrode
CenSCIR	Center for Sensed Critical Infrastructure Research
CMU	Carnegie Mellon University
F_{cy}	Processor Clock Source
F_{OSC}	Internal Oscillator Frequency
FR	First Responders
FREM	First Responder External Measurement Unit
GPPS	Global Positioning System
IC	Integrated circuit
IDAD	Instituto Do Ambiente E Desenvolvimento
IEETA	*Instituto de engenharia electrónica e telemática de Aveiro*
INESC	Technology & Science Associate Laboratory
IR	Infra-Red
IT	*Institudo das Telecomunicações*
LII	Lower Limit of Flammability
LSI	Higher Limit of Flammability
NACK	Not Acknowledge Condition
OSHA	Occupational Safety and Health Administration
OT	Operation Theatre
PCB	Printed Circuit Board
PEL	Permissible Exposure Limit
PID	Photoionization Detector
PGA	Programmable-gain amplifier
PPL	Phase Lock Loop
PPM	Parts per Million
RE	Reference Electrode
SCBA	Self-contained breathing apparatus Open-circuit
T_{cy}	Instruction Cycle Period
UART	Universal Asynchronous Receiver/Transmitter
VJ	Vital Jacket
VH	Vital Helmet
VR	Vital Responder
WE	Working Electrode

Chapter 1

Introduction

1.1 Context and Motivation

The present work addresses a project hereon named *Vital Helmet* (VH), which itself is part of *Vital Responder* (VR), a large-scale, multi-disciplinary and multi-institution research project.

The VR's main objective is to explore synergies between new technologies capable of being completely integrated, such as networks of sensors, intelligent buildings, wearable technologies and other location services. All this in order to assure a system in emergency contexts that can be safe, reliable and effective [1].

In accordance to VR's line of smart and wearable technologies, the development of a sensorized helmet module for firefighters was proposed. This module should be able to adapt to different fire scenarios —such as chemical industries, refineries, plastic industries, forest fires, etc.— in order to measure the concentration of dangerous substances in the environment. Naturally, some data processing would be still required to determine if the ambient is safe and to certify the firefighter's exposition is within the limits established by the health-regulation institutions.

Being a fireman means performing one of the most dangerous jobs in the world [2], so this project together with *Vital Responder*, fits perfectly for their mission. And although this project is specifically oriented towards firemen, it is expected that the helmet module can be used and adapted to others jobs such as miners or policemen.

In Portugal, firemen are ruled by the National Authority for Civil Protection (ANPC) and perform functions that range from prehospital services to cutting vehicles apart during car accidents. Evidently, fire fighting is also an immense part of their tasks, and it will be upon the latest that this project will be focused. More specifically, the type of fires to be considered over this thesis will be urban, industrial and forest.

Firemen are trained for critical and demanding scenarios of fire, smoke and lack of visibility so they can save lives. Gas leaks and dangerous substances spills are other non-fire related risks of this job.

Facing an operating theater (OT) of thick smoke, high flames and high temperatures can lead to many health problems and accidents such as burns, smother or injuries caused by structures' collapse. Long term exposure to hazardous gases can also lead to other health issues such breathing problems and heart attacks.

According to information given by ANPC, there are about 5900 house fires per year. According to the same information, 2010 has been the worst year in terms of disasters[3].

Regarding the forest fires, the annual average since 1980 is 3 deaths. The most deadly year was 2013, with a total of 9 deaths. As an attempt to lower this fatality numbers and to protect those who save the civil population, this project intends to prevent work-related accidents in fire brigades.

In Table 1.1, number of injured firefighters between 2005 and 2007 is represented. As we can conclude, the most dangerous activity is the rural fires. Thus, and despite the number of injuries is decreasing, these are the focus of this dissertation, continuing so this evolution in firemen's health. As shown in Fig. 1.1, the number of firefighters' deaths worrisome data. As we told before, it is of ours interest reduce as much as possible this numbers.

Table 1.1: Evolution of the number of injured firefighters between 2005 and 2007 [4]

Evolution of the number of injured firefighters between 2005 and 2007

Occurrence	2005	2006	2007	TOTAL	%
Rural fire	818	281	179	1.278	46.2
Urban fires	97	51	70	218	7.9
Industrial fires	35	68	60	163	5.9
Traffic accidents	155	175	142	472	17,0
Workplace accidents	102	180	101	383	13.8
Health emergencies	6	68	181	255	9.2
Total	**1.213**	**823**	**733**	**2.769**	

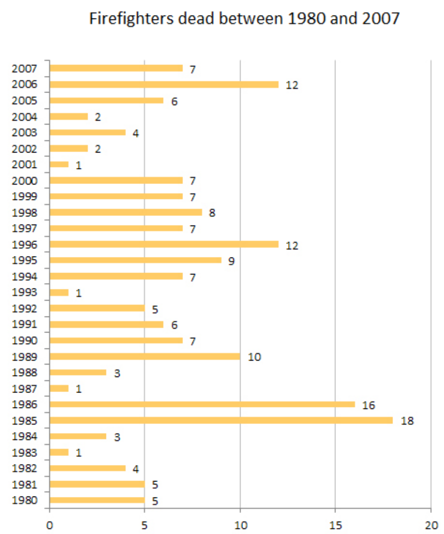


Figure 1.1: Firefighters dead between 1980 and 2007[4]

We tried insistently to obtain more recent statistical data. To do that, we try the telephone contact and we sent several e-mails to the ANPC, as demonstrated in Appendix A.1, always without answer.

1.2 Objectives

The main objective of this thesis is to develop and implement a sensorized helmet module, designed specifically for firemen, which monitors and assesses the concentration of dangerous gas substances in the operation theater. Fig. 1.2 shows a conceptual diagram of the project.

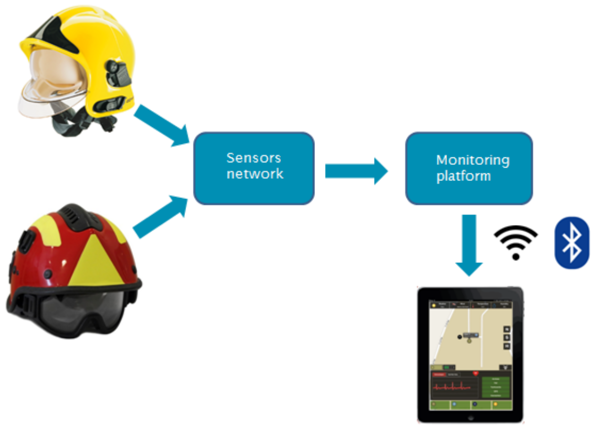


Figure 1.2: Conceptual diagram to be implemented

One of the aims of the project *Vital Responder* is exactly to study the relation between sensors and innovative technologies capable of being adapted to clothes to get reliable and safe systems to be used by *First Responders*. The VR's main scope is to reach the system in real time contexts under adverse conditions and monitor data online.

The main goal of the *Vital Helmet* is to build a helmet module which is flexible to different fire contexts and in which you only have to change sensors according to the type of fire: forest, urban or industrial. Thus, the software should be reprogrammed and readjusted. To sum up, the key idea is to redesign the hardware and firmware to different contexts.

In case there is danger to the firemen, an alert should be sent to FF and to the operational command service.

To achieve this goal, the following topics have been planned:

- Identify the best sensors
- Design a hardware module adaptable to different sets of sensors
- Programming a microcontroller to be able of gas monitoring
- Implementation and assessment of the developed system in the lab
- If possible, evaluate the design in real sets

1.3 Document Structure

This dissertation is divided in 6 chapters. In this chapter, motivation and its aims have been presented. Chapter 2 will rely on a brief approach to urban and industrial fire as well as the state of art regarding to monitoring of gases technology. Chapter 3 provides a description of our solution and its specifications. The system development will be discuss on Chapter 4. Then, in Chapter 5 the testbed for the proposed solution is described and the theoretical and experimental evaluation is presented. Finally, in Chapter 6 conclusions of this work are drawn.

Chapter 2

Existing Market Solutions

2.1 Introduction

Along with the increase of industrialization, grew the need to prevent not only disasters in forest fires but also in housing and industries. In this chapter, we will present an overview of the existing solutions for gas monitorization during fires, listing their advantages and drawbacks in the context of our work.

Among the different available commercial solutions, and according to my experience as a firefighter, Dräger and MSA are the brands that provide to monitoring solutions preferred by firefighter departments. Such solutions allow a multi-gas monitoring in situ and it is possible to recalibrate the sensors to detect different gases at different times. However, these solutions are unseemly to distinct scenes and little practical in terms of transportation or used by firemen.

Bearing this fact in mind, devices and sensors offered by these enterprises have been studied in the area of fire departments and accidents with dangerous substances.

There is no personalized solution to different scenarios that stores the information about every fireman on the fire scene for an external supervisor to monitor its team.

Such conclusions arose the need to develop a system that conjugates the possibility to personalize and the accuracy of the existing solutions, but to be integrated in a vital-signal monitoring solution in which our research group is actively working: the Vital Responder Project.

2.2 Firefighters and Fires

Urban fire is defined as the combustion without control in space and time of the fuel material in buildings including parts of elements of construction and coating. The same type of accident in an industrial building is referred to as industrial fire [5].

In such type of fires, the first stage is called search and rescue and it aims to search and find victims and obtain information about the extension of the fire. This stage is completed without fighting the fire and so firemen are completely exposed to gases and smoke.

On the other hand, although they do not occur so often as fire does, firemen also have to face rescues confined to limit space. We consider confined space every space that has the following features:

- Dimension and configuration in which a person enters and performs a certain job
- Limited means of access
- Inappropriate place for permanent human occupation [6]

These places have some dangers, for example, they may contain conditions for a dangerous set, have substances which can trap a person or even the configuration of the space can preclude the firemen to leave out [6].

Urban and industrial fires as well as rescue in confined spaces have adjacent dangers such as atmosphere weak in oxygen, lack of brightness and high temperature. Other danger to be aware is the possibility of toxic and/or flammable atmosphere [6].

Facing these facts, the firemen have to use the individual equipment of protection. As it is seen in Fig. 2.1, this is composed by the NOMEX (registered trademark for flame-resistant material) suit, helmet, glasses or visor, gloves, safety personal alarm, self-contained breathing apparatus open-circuit (SCBA) and boots.

Figure 2.1: Individual protective equipment[7]

Another adverse situation experienced by firemen are catastrophes lived in environments with dangerous substances.

Dangerous substance are considered to be any substance (raw material, product, subproduct residue or intermediate product) that considering its characteristics can cause harm to humans, animal or environment health [8].

The risks are mainly due to the training in dangerous atmospheres such as the toxic and explosive ones.

An explosive atmosphere is the one which contains gases or flammable vapor or mixed fuels with air in percentages within the limits of flammability or explosivity [8].

Each fuel has its owns limits of flammability, i.e., the scale of values from which it is possible the beginning of combustion according to the norm NP- 3874-1 (1995). An example can be seen in Fig. 2.2.

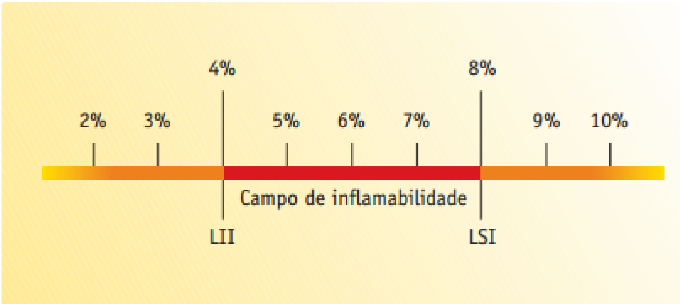


Figure 2.2: Flammable field of an hypothetical fuel [9]

The **Lower Limit of Flammability, LII** means the minimum percentage of gas, which mixed with air, allows a combustion. Below this limit, it is impossible occurs this phenomenon.

Oppositely, the **Higher Limit of Flammability** is the maximum percentage of gas, which mixed with air, allows a combustion. Above this limit, it is impossible occurs this phenomenon.

On the Table 2.1 the field of flammability of some components its documented.

Table 2.1: Flammable fields of various fuels [9]

Fuel	**LII(%)**	**LSI(%)**
Acetylene	2.5	82.0
Alcohol (vapor)	3.3	19.0
Ether (vapor)	1.7	48.0
Gasoline(vapor)	1.4	7.6
Hydrogen	4.0	75.0
Propane	2.1	9.5

The existence of an atmosphere or explosive mixture can be measured with the help of an explosive indicator. These devices emit light and voiced signals whenever the concentration of gases or vapor is higher than LII [8].

A toxic atmosphere is the relative ability of a substance causing injury to the biological tissues due to the existence of a toxic substance in the air able to cause serious acute or chronic injuries or even death by inhalation or other mean [8]. These atmospheres are very common in chemical products factory fire or pesticide warehouses.

Because these types of substances are extremely dangerous even in small concentrations, they are expressed in parts per million (ppm) and not in percentage, being $1ppm = 0.0001\%$.

Table 2.2 portrays toxicity of various combustion gases.

The permissible exposure limit (PEL) was studied, nationally and internationally, more specifically in USA and California. For the latter two cases, the *Occupational Safety & Health Administration* was consulted. As the name implies, it is the USA federal agency which regulates health

Table 2.2: Toxicity, in PPM of various gases of combustion [9]

Substance	Permissible many hours	Dangers in half an hour	Mortal
Ammonia, NH_3	100	500	2500 to 5000
Carbon dioxide, CO_2	1000 to 1500	3500 to 4000	60000 to 70000
Carbon monoxide, CO	100	1500 to 2000	10000
Chlorine, Cl_2	0.35 to 1.0	40 to 60	1000
Hydrochloric acid, HCl	10	1000 to 2000	1300 to 2000
Hydrogen cyanide, HCN	15	100	180 to 270
Hydrogen sulfide, H_2S	20	300	1000
Nitrogen oxides, NO/NO_2	10 to 40	100 to 150	200 to 700
Phosgene, $COCl_2$	1.0	25	50

and safety in the workplace. Nationally, this regulation is led by *Agência Europeia para a Segurança e Saúde no Trabalho (EU-OSHA)*.

This study can be consulted in Table 2.3.

Ordinarily, PEL is expressed as a time weighted average. This is the average exposure over a certain period of time, usually a nominal eight hours (TWA). However, it is also possible manifest the PEL as a short period (STEL). STEL is average exposure acceptable for a short period, typically 15 minutes, while the weighted average time is not exceeded. Finally, *CEILING* is the limit that can not be exceeded for any length of time and is applied to irritating gases and materials that have immediate effect.

Table 2.3: Permissible exposure limits, PPM, of some gases [10] [11]

	OSHA			**OSHA -Califórnia**			**EASHW (PT-IPQ)**		
	Permissible Exposure Limits			Permissible Exposure Limits			Permissible Exposure Limits		
	STEL	TWA	CEILING	STEL	TWA	CEILING	STEL	TWA	CEILING
Acetylene, C2H2	*	*	*	*	*	*	*	*	*
Ammonia, NH3	35	25	-	35	25	-	35	25	-
Butane, C4H10	n.d	n.d	n.d	n.d	n.d	n.d	n.d	1000	n.d
Carbon dioxide, CO2	30000	5000	-	30000	5000	-	3000	5000	-
Carbon Monoxide, CO	-	50	-	-	25	200	-	25	-
Chlorine, Cl	-	-	1	1	0.5	-	1	0.5	-
Cellulose	-	10mg/m^3	-	-	10mg/m^3	-	-	10mg/m^3	10mg/m^3
Gasoline	n.d	n.d	n.d	n.d	n.d	n.d	500	300	n.d
Hydrogen cyanide, HCN	-	10	-	-	-	4.7	-	-	4.7
Hydrogen sulfide, H2S	-	-	20	15	10	50	15	10	-
Methane, CH4	n.d	n.d	n.d	n.d	n.d	n.d	-	1000	-
Nitrogen dioxide, NO2	-	-	5	1	-	-	5	3	-
Sulfur dioxide, SO2	5	-	-	5	2	-	5	2	-

The word gas means the physical state of a substance that with normal pressure and temperature conditions (ptn -1 atmosphere and 25 °C), it has no shape in volume but it acquires shape and occupies the total part of the volume of the container or the container space [8].

There are flammable gases, inert, reactive, oxidant and toxic among others.

Flammable gases can lead to fire and it can also lead to fire if it happens in a closed space.

The inert gases are those which do not react chemically with other substances. As opposed to these, reactive gases have chemical incompatibility with each other. The oxidizing gases are not flammable themselves but they can contribute to the combustion and finally the toxic gases are those which leads to adverse effects to human health.

One of the most risky dangers which firemen face is *Bleve*. These phenomena which can be seen in Fig. 2.3, represents the explosion that can happen when a container with a gas or a confined vapor breaks during a fire.

Figure 2.3: Bleve of a deposit

Gases used in industry have higher probability of getting involved in accidents which require the firemen intervention.

In Table 2.4 there are some characteristics of three of the most gases in industry.

Table 2.4: Characteristics of the most 3 common gases in industry [8]

	Acetylene	**Chlorine**	**Hydrogen**
Assessent	Reactive Flammable Compressed	Reactive Non-Flammable Molten Toxic	Flammable Compressed Criogenic
Ebullition	-84ºC	-30ºC	-253ºC
Flammable area	LII = 2.5% LSI=82%	Non applicable	LII = 4.0% LSI=75%

Compressed gases are those that can be stored in a container. Liquefied gases are the kind of gases able to become liquids at normal temperatures when they are inside cylinders under pressure [12].

In case the gas remains liquid at low temperatures it is a cryogenic gas.

2.3 Monitoring Hazardous Materials

Nowadays monitoring dangerous substances in Portuguese fire departments is done through complementary devices to the individual protection and mainly to Dräger and MSA.

These can detect only one or various gases. However, the modules are unseemly to different scenes and little practical in terms of transportation or used by firemen.

2.3.1 Dräger Technology

Dräger offers gases measurement devices to monitor each area individually. In what concerns gases detectors, Dräger offers 5 devices of multi-gas detection and 3 of single-gas detection.

2.3.1.1 Dräger X-am®5000

Dräger X-am®5000 is used for self protection and can detect from 1 to 5 gases.

This device is equipped with a recent Dräger sensor generation electrochemical of high profit of the XX_s minimized generation as these sensors are long lasting ones.

Besides being able to measure O_2, CO e H_2S, it is also capable of detecting CO_2, Cl_2, HCN, NH_3, NO_2, PH_3, SO_2 and organic vapor.

One of the main advantages of this device is the flexibility adaptable to sensors being easily rebuilt, recovered or recalibrated to detect other types of gas.

Another characteristic of it is the advanced precision in detecting dangerous gases.

In terms of temperature, it can bear until the value scales of $-20\,^{\circ}$C e $+50\,^{\circ}$C.

The Dräger X-am®5000 cost around €1000.

Figure 2.4: Dräger X-am®5000 [13]

2.3.1.2 Dräger Multi-PID 2

Dräger Multi-PID 2 is based on the detection of photoionization and it is used with volatile organic compounds.

PID (photoionization detector) is a type of sensitive sensor that has a very fast response time. Due to its precision it is considered the preferable sensor when dealing with low concentration. This type of sensor can measure volatile organic compounds and other gases in concentration around parts per billion.

The main advantage is the wide amplitude of measurement. A measure of 20.000 ppm can be achieved if it is used an optional probe of gas dilution.

Figure 2.5: Dräger Multi-PID 2 [13]

A gas library embrace up to 70 substances is saved in the device. In addition to these, an additional 60 substances can be identified and entered into the device if required.

It is possible to track the air, soil and contaminated liquids as well as make leaks measurements in enclosed spaces [13].

Multi-PID 2 cost around €4500.

2.3.1.3 Dräger Pac®7000

Dräger Pac®7000 is a compact gas detector, robust and of long durability. This way it is appropriate to firemen needs once it has a protective rubber resistant to impacts. The equipment also guarantees the protection against water and dust as well as an optimization of the electromagnetic resistance. In relation to its durability, this device has an endless life [13].

Figure 2.6: Dräger Pac®7000 [13]

If the alarm limit exceeds the oxygen concentration established, a triple alarm (sonorous, luminous and visual) is set up.

A disadvantage of this solution is only to detect one gas. The sensors which belong to this device are Dräger sensor XX_s, quick and reliable answer sensors.

In order to have maximum safety, the sensor is located inside the box to allow the gas to come in from the upper side and to the front assuring the correct measurement even if the gas entrance was accidentally blocked [13].

This device cost around €500.

2.3.2 Dräger Sensors

A sensor is known as any component or electronic circuit which permits the analysis of a specific environment condition. This one can be simple such as the temperature or brightness. A more complex step would be the rotation of an engine or the distance of a car to a near obstacle or even distant events of our daily life such as the detection of subatomic particles and cosmic radiation [14].

Table 2.5: Main advantages of sensors used by Dräger [13]

	Advantages
PID	Reliable detection of toxic substances
IV	Do not poison as the traditional catalytic sensors Higher level of accuracy
Catalytic	Various gases at the same time
XXs	Long term excellent stability and quick answer High sensitivity and refined gas selection

(a) PID Sensor (b) IR sensor (c) Catalytic Sensor (d) XXs Sensor

Figure 2.7: Dräger Sensors [13]

Some gases and vapors are toxic to human beings even below the LEL. For this reason, PID sensors are essential to measure ppm levels of volatile organic compounds.

As we can observe in Fig. 2.8, as the gas enters the device, the air is forced into the measure chamber and subjected to an electrical field that promotes its ionization by the production of photons. Once the basic compounds of the air (like noble gas, oxygen, carbon dioxide, water vapor and nitrogen) require higher energy to be ionized, the first molecules to be affected in this process are the hazardous substances that might be present in the air. In fact, most of the organic compounds known as dangerous are ionized and subjected to the electrical field in the measure chamber. The concentration of the hazardous substances present in the air is determined by the direct proportionality between the intensity of electrical current and quantity of ionized molecules.

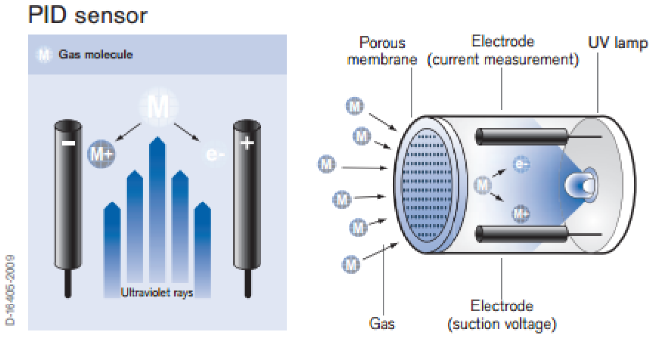


Figure 2.8: PID Sensor [13]

2.3.2.1 Software Vision 32

Dräger presents a monitoring software of gases, Vision 32, able to show in the chart all the essential guidelines of the systems. The signal information is transmitted via serial interface (RS-232, RS422/RS-485) from the Regard Modbus Gateway card, to the PC and displayed by this software.

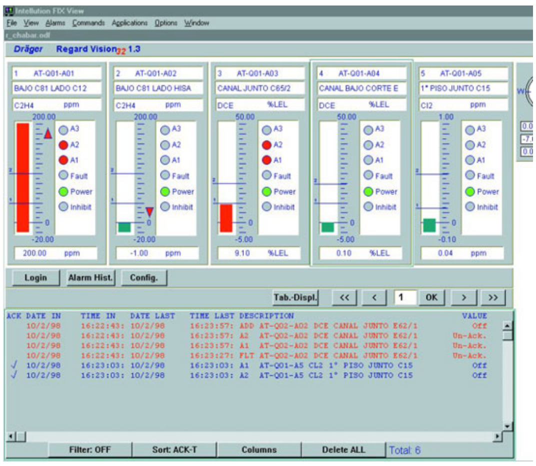


Figure 2.9: Software Vision 32 [13]

This software offers the possibility of visualizing:

- General vision of the complete layout of the facilities
- Point-to-point information
- Real concentration of gas
- Functional states such as calibration, alert or failure conditions
- Alarms [13]

2.3.3 MSA Technology

MSA is another brand which is very used by firemen. It is recognized as a safe, reliable and innovating brand by fire departments.

2.3.3.1 Multi-Gas Detector with Internal Pump ALTAIR®5x

Figure 2.10: MSA Multi-gas Detector with ALTAIR®bomb [15]

Characteristics and benefits:

ALTAIR®5x is a multi-gas detector to 6 different gases and integrated and illustrated bomb, CO_2, CH_4, C_3H_8, C_4H_{10}, among others.

According to fuel gases, this device uses catalytic or infra-red sensors and concerning oxygen measurement and toxic gases, electrochemical or infra-red sensors are used.

This device has a triple alarm system (sonorous, luminous and vibratory) and automatically detects lack of movement alerting to risky situations like immobilization or accident;

It is also dressed by polycarbonate to protect the detector of falls until 3 meters.

Shows simultaneously the analysis that sensors do, battery level, indicates the answer test validation and indicator of life ending of sensors calling the user attention to the need of adjusting or changing the sensor.

In terms of temperatures, works a value scales between $-20\,^{\circ}\mathrm{C}$ to $+50\,^{\circ}\mathrm{C}$

This multi-gas detector has sensors with long durability (more than 4 years to sensors of O_2, CO/H_2S and SO_2 and 3 years more to NH_3 and Cl_2) [15].

The price of this solution is around €1700.

2.3.3.2 Multi-Gas Detector SIRIUS®

Features and benefits:

Besides measuring fuels, toxic gases and lack of oxygen, this solution also monitors volatile organic components simultaneously;

PID mode can be switched off if it only needs the multi-gas detector;

Figure 2.11: SIRIUS®Multi-gas Detector

This multi-gas detector has voiced and visual alarm as well as self-calibration [15]

The price of this device is around €4000.

2.3.3.3 Single Gas Detector ALTAIR®Pro

Figure 2.12: ALTAIR®Pro Single-Gas Detector [15]

Features and benefits:

Single Gas Detector ALTAIR®Pro has capacity of detecting O_2, CO, H_2S, NH_3, NO_2, PH_3, SO_2, HCN, Cl_2 and ClO_2.

The monitor shows the concentration of gas as well as the oxygen percentage;

It is possible to record the last 50 alarms and sudden changes in gas concentration as well as reprogram the alarms.

This device is the simplest and cheaper one. It costs around €450.

2.3.4 Alphasense

Alphasense is a gas sensor development and manufacturing company. This group provides innovative solutions to specific customer industrial market.

The main goal of Alphasense is helping to keep a safer, cleaner and more energy efficient world through sensor technology.

This company is working with universities and research establishments worldwide in order to be aware of innovation.

The sensors available for this company are listed below:

Figure 2.13: Alphasense's sensors [16]

- Carbon Dioxide
- Carbon Monoxide
- Chlorine
- Dust and Particles
- Miniatures
- Nitrogen Dioxide
- Oxygen
- Pellistors
- Sulfur Dioxide

Each sensor of Alphasense is tested for a long-term reliability. Other advantage using Alphasense's sensor is the high quality and high performance, producing sensors to use not only in fixed site applications but also in industry market.

2.4 Vital Responder Project

"Monitoring Stress among First Responder professionals is a Carnegie Mellon University(CMU)-Portugal funded project with the main goal to provide secure, reliable and effective first-response systems in critical emergency scenarios. To achieve this goal an interdisciplinary team with expertise in areas such as wearable technology for vital signs, biomedical signal processing, sensor networks and RF Location/Intelligent buildings was formed"[1].

Funded by Carnegie-Mellon - Portugal / FCT in July 1st 2009, this project is a partnership between the IEETA from Aveiro University and INESC-TEC Porto, being Prof. Dr João Paulo Cunha the principal investigator. There are some other partners such as IT, Biodevices and CenSCIR.

VR project has been tackling the lack of real-time monitoring and decision technologies that can lead to in-depth knowledge of the physiological stress processes at first responders and its health consequences thereof.

First Responders experience high levels of stress and fatigue which leads to some coronary disease [17]. Another important aspect is the fact cardiovascular deaths in FR is higher and earlier than average population [18]. Thus, the principal objective of this project, as written before, is to provide secure and avoid earlier diseases and deaths.

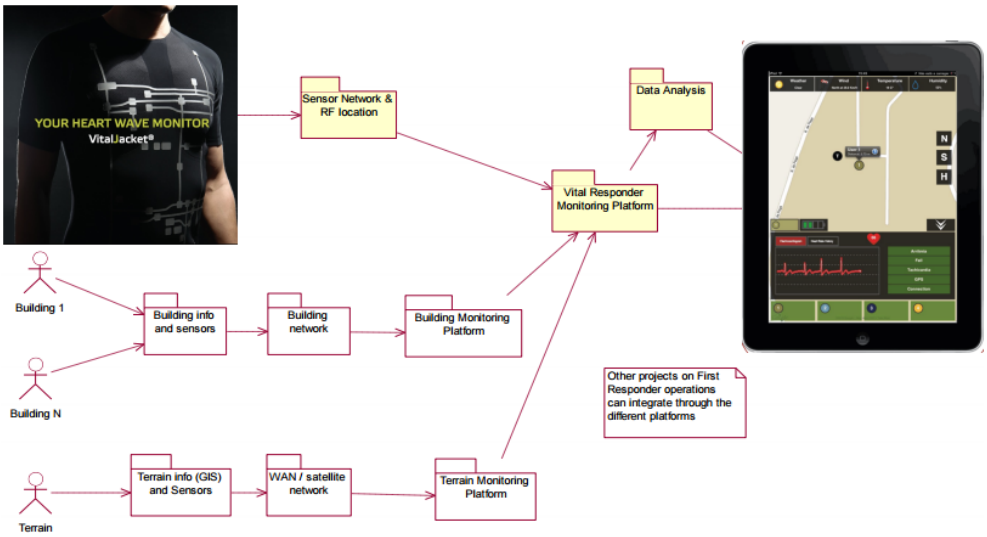


Figure 2.14: Vital Responder®system overview

As can be seen in Fig. 2.14, there are several areas under study such as: **Wearable Technology**, **Sensor net**, **Multimedia Integration** and **Data Analysis**. This project is an interrelation between the Wearable Technology and Sensor networks.

Wearable technology is in constant development and, nowadays, it plays a crucial role supporting healthcare institutions such as hospitals, fire departments and police. Furthermore, new technologies are converging to support this purpose of adapting the treatments and therapies for each patient.

The Vital Responder Project had its beginning with *Vital*, a conceptual architecture on health and wellbeing monitoring. This could be set up to measure vital signals (ECG, temperature, respiration, movement/fall, posture, actigraphy, oxygen saturation, etc.) and psycho-social variables (panic button, medication delivery, activity habits, location, etc.) using wearable or bed-side sensors [19].

The next step under this project was develop the earlier thought to wearable sensors. This question leads to the first prototype called *Vital Jacket*.

2.4.1 *Vital Jacket®*

After some years improving it, VJ was licensed in 2007 to Biodevices S.A. The certification was concluded in 2009 according to the standards ISO9001 and ISO13485. It was also certificated as "ambulatory device", compliance with the MDD directive 42/93/CE that regulates medical devices in Europe.

There are two types of VJ, a commercial version and a SDK version. In both cases, it is possible send clinical quality ECG, heart rate and actigraphy data through Bluetooth wireless connection to a smartphone or PC that has a Bluetooth channel [19]. In the last one, the Vital Jacket®Cardio, has 1 or 5 ECG leads and a 3 axis accelerometer, allowing a correlation between ECG and user's level of activity. As we can see in Fig. 2.15, it is possible collect data into an SD memory card for offline analysis. Other important application, also represented in Fig. 2.15, is the real-time analysis. The data can be send to a PDA, PC or even to a cardiology information system, being in the latter case the information sent through wireless LAN, GPRS, 3G or 4G mobile data networks.

"To our knowledge, this is the first truly wearable cardiology long term ambulatory monitor to hold such certification worldwide" [19].

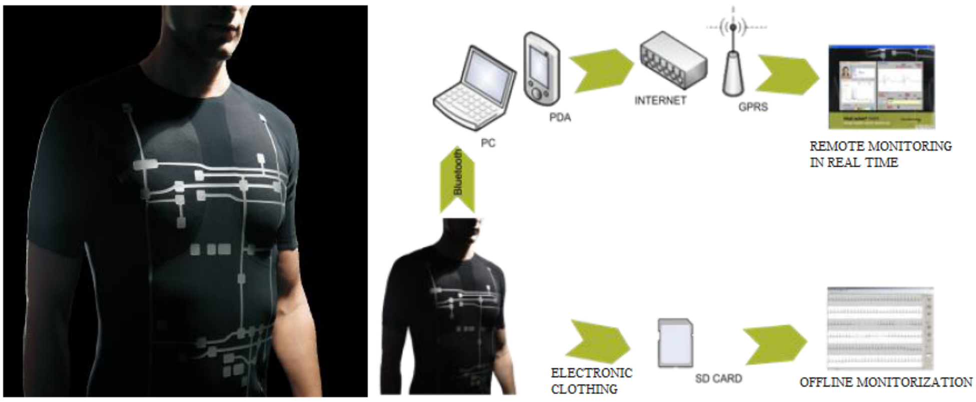


Figure 2.15: The commercial version of the Vital Jacket®

2.4.1.1 Vital Jacket for First Responders: Vital Responder

After some studies of firefighters in action, and understanding all the risk this job entails, a new version of *Vital Jacket* was developed, the *Vital Responder*. Since the previous version of VJ has a mixture of elastane (28%) and polyamide (62%) and elastane is heat sensitive (potentially causing burns) was necessary to solve this situation recreating the t-shirt with lower concentrations of elastane in order to be used in a fire scenario. Thus, and following international regulations, the firefighter's clothes has to be made with less than 2% of elastane. This problem force to remake embedding micro-cabling and micro-electronic systems.

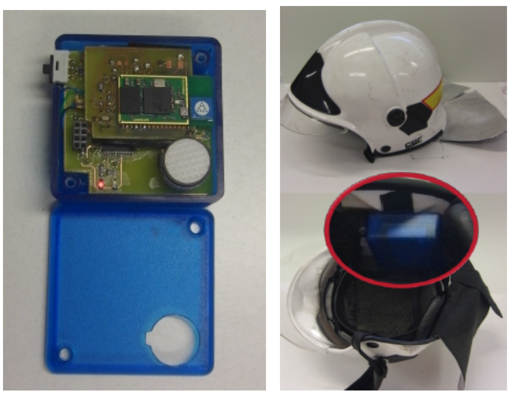
Figure 2.16: Vital Responder

Furthermore, and in order to follow all the international and Portuguese standards the new Vital Jacket version has incorporated cotton instead of polyamides.

In short, the *Vital Responder* has only 98% of cotton and 2% of elastane [19].

2.4.2 FREMU

The work presented in this document was developed in the context of *FREMU*, an ongoing project in which the group is involved.



(a) FREMU (b) FREMU localization

Figure 2.17: Wearable Tech: Helmet Unit v1

This unit allows measuring:

- Altitude estimation (m)
- Barometric Pressure (hPa)
- Carbon Monoxide (CO)
- Temperature ($^\circ$)

Nevertheless, this unit only measures one type of sensor and its not possible change it. Furthermore, the CO sensor is not for industry standard but to home use, i.e, lower concentration of gases.

Keeping this in mind, a new version has been planned: the *Vital Helmet*.

2.5 Discussion

In this chapter we presented the research work that has been done in the field of monitoring gas in a fire environment. As we observed, there are two principal brands, Dräger and MSA used by fire departments. However, these only produces additional devices to the individual protective equipment which complicates firefighter's mobility.

This helmet allows firefighters to put and use several sensors in it. There is a master board and in it the firefighter can put a plate with a set of sensors. If today the firefighter faces a forest fire, probably he/she would want to monitoring CO, CO2 and NO2 but if he/she faces an industrial fire, he/she would want to use another set of sensors. This helmet is prepared to serve these different situations. Master adapts itself to any type of sensor and as far as it is known this feature does not exist yet in the market.

Thus, and following the development of the VR wearable platform, this dissertation aims at the evolution of the helmet module with a hardware sensing architecture allowing different sets of environmental sensors adaptable to different critical scenarios.

To develop the helmet module, we will use the Alphasense's sensor since they manufacture portable sensors. Besides its high quality, another reason for this choice was the existence of industry standard size for portable gas detectors.

As an attempt to lower the fatality numbers observed in recent years and to protect those who protect the civil population, this project intends to prevent work-related accidents in fire brigades.

Chapter 3

Proposed Solution

This chapter presents a description of the *Vital Helmet* solution based on gas sensors. First we make a brief overview of the systems we want to implement. Then the scenarios we want to cover with this solution will be analyzed. Finally, it is presented an architecture for this proposal, including hardware and some firmware specifications.

3.1 System Overview

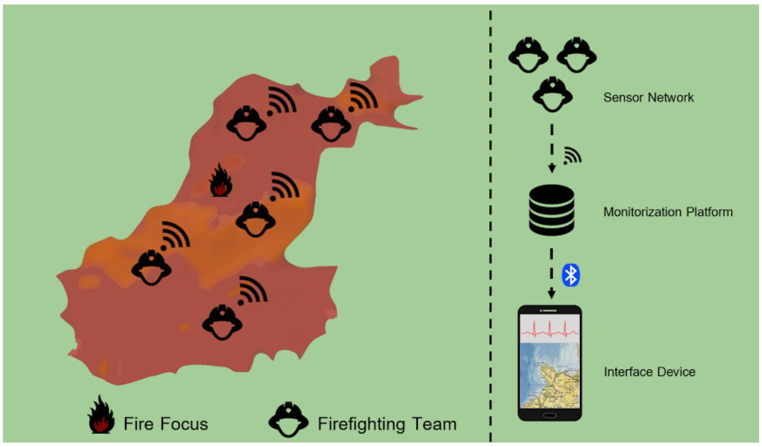


Figure 3.1: General system overview

As mentioned before, this dissertation is part of the *Vital Responder* project. Our research group is currently part of an international project for the monitoring of firefighters in action. One of the most relevant parameters to evaluate, since it leads more easily to death, is the concentration of potentially toxic gases, which is the aim of this thesis. Thus, we propose a major novelty on the gas monitoring and to the best of our knowledge we are involved in the single one project that provide an adaptable solution to the emergency scenario. Since the firefighters work under pressure and a quick response is mandatory, it is not expectable that they change the sensors at the moment of the occurrence. Thus, we created a *flexible boxes* concept, i.e, the firefighter department can have a forest box with CO, CO_2 and NO_2, as example, and a urban box with other gases such as methane and propane. Fig. 3.1 shows a hypothetical fire scenario. As can be seen, it is expected sending the gathered data to an interface device. Thus, both fireman and his/her chief can be aware in case of a dangerous situation.

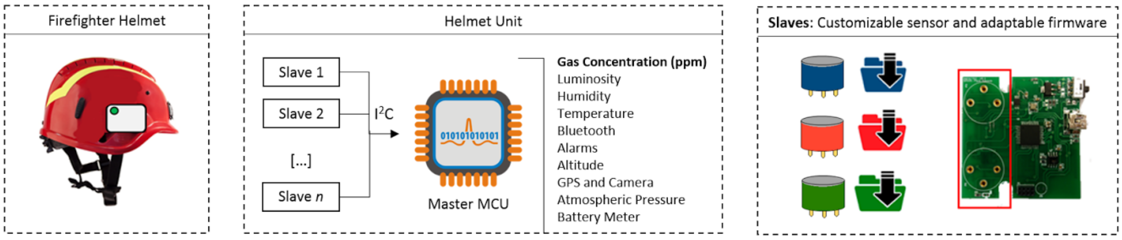


Figure 3.2: Proposed Solution

In order to help the firefighter mobility, the system in Fig. 3.2 presented is expected to be incorporated into a broader sensing solution, *Vital Helmet*: a box to be held on the firefighter helmet and that measures luminosity, humidity, temperature, altitude, atmospheric pressure, has GPS and camera. These measurements are of great importance because these environment variables can cause several injuries in a human being. For example, measure the luminosity and humidity are important types of information, since the chief is not always near to the team nor he is able to assess the in-situ conditions of the fire brigade. In some cases, the firefighter only realizes how high the temperature is when the helmet begins to melt. Thus, measuring the temperature is crucial. On the other hand, high altitudes or low atmospheric pressure locations can be a serious risk to the firefighter's team. Hence, it is of major importance be aware of these variables. The GPS and camera are essential for the chief to realize where his team is and in what conditions they are working.

Having localized and extensive information of the environment conditions allow a better and personalized response to each firefighter, leading to lower levels of accidents and deaths. Furthermore, to develop a customizable and adaptable solution, a slave module was proposed, i.e., a module which has its owns processing and firmware. The gas monitorization is done in this module and then data is sent to the master. To be able to accept several types of gas sensors, each slave has its own microcontroller. Thus, we have local processing - in the sensor. The slave has to integrate the signal during 15 minutes and 8 hours and, in case the gases' concentration exceeds the legally permissible limit, a condition alarm must be sent to the master.

The communication between the slave and master will be done through I^2C. This protocol will be explained later in the next chapter.

3.2 System Architecture

As we can observe in Fig. 3.3, this system is mainly composed of a sensor, an IC potentiostat, an external ADC (optional) and a microcontroller. An external ADC is facultative since the system keep working correctly without it, however, with a lower precision. For example, the CO sensor

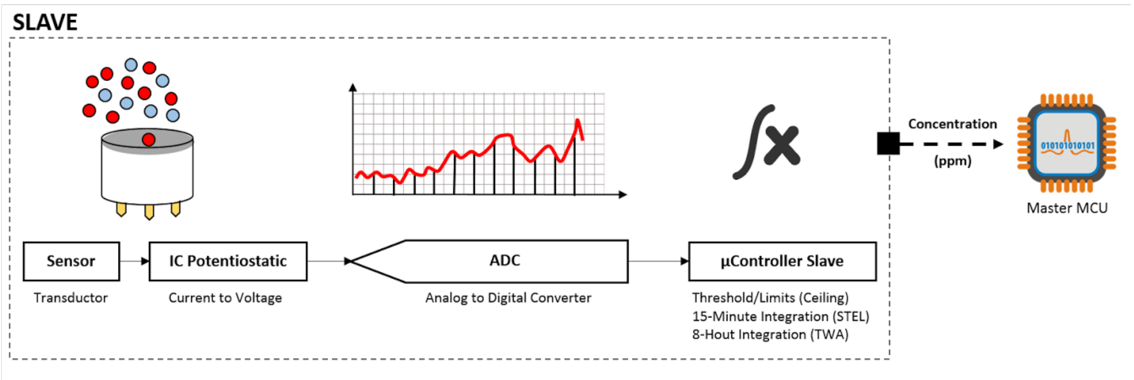


Figure 3.3: System Architecture

has a full scale of 100000 ppm, use a 20-bit ADC instead of 16-bit ADC the gain is only about 0.5ppm. The sensor, as a transducer it is, converts a non-electric information (gas concentration) to an electric one (current). Then, a configurable analog front-end (AFE) potentiostat for low-power chemical sensing applications, the LMP91000 from *Texas Instruments*, will provide a complete signal path solution between a sensor and a microcontroller that generates an output voltage proportional to the cell current. After the LMP, the signal can be processed by the microcontroller's ADC or, in case the sensor full scale is too high, an extern ADC can be used before it. This is an optional decision since the system works properly without it, however , not having the best possible resolution. This issue will be discussed later in this chapter. Finally, the microcontroller unit (MCU) must analyze the signal received, intregate it, and, if necessary, send a condition alert to the master's MCU.

3.2.1 Sensors

As a starting point, and according to my experience, a set of sensors were grouped in accordance with the type of emergency.
On the chart bellow, some examples are evidenced in agreement with the type of emergency.

Having the solution here presented in their fire departments, firefighters can have modules of set sensors conforming to the time of year or even change the sensors depending on the emergency scenario. All of these sensors are required for a complete monitorization, although , because of portability issues the number of sensors must be reduced to 2/3 sensors to stand up the worst scenario, i.e, the most toxic gases or gases that have the lower PELs. Table 3.1 displays the most common gases in each type of industries.

Choosing a sensor, specially a sensor to be used in a fire scenario has a lot of requirements to fulfill, such as:

- high range and overgas limit (to prevent easily saturate)
- linear over a wide range
- low noise

Table 3.1: Set of sensors according the type of emergency [8] [5] [20]

Industry	Dangerous Gases
Agriculture	Explosives, O2, NH3, CO2, CO, H2S, NO, NO2, PH3
Aviation	Explosives, O2, CO2, CO, COVs
Building and Construction	Explosives, O2, CO, H2S, NO, NO2, O3, SO2
Chemical	Explosives, O2, NH3, CO, CL2, H2, HCL, H2S, NO, NO2, SO2, COVs
Construction	Explosives, O2, CO, H2S, NO, NO2, COVs
ETA/ETAR Water	Explosives, O2, NH3, CO, CL2, H2S, O3, SO2, VOCs
Food/Drinks	Explosives, O2, NH3, CO2, CO, HCL, HCN, H2S, PH3
Forest Fire	CO, CO2, NO2
Metallurgical	Explosives, O2, CO, HCN, H2S, NO, NO2, SO2, COVs
Mines	Explosives, O2, CO2, CO, HCN, H2S, NO, NO2
Naval	Explosives, O2, CO2, CO, H2S
Paper	Explosives, O2, NH3, CO, CL2, CLO2, H2S, SO2, VOCs
Petrochemical	Explosives, O2, NH3, CO, H2S, COVs
Pharmaceutics	Explosives, O2, NH3, CL2, HCL, H2S, SO2, VOCs
Power Station	Explosives, O2, NH3, CO2, CO, H2, H2S, SO2
Urban Fire	CO, CH4, C4H10
Welding	Explosives, O2, NH3, CO2, CO, HCL, HCN, H2S, PH3

- low sensitivity to other gases
- high temperature range

Thus, the *Alphasense sensors* were chosen. Regarding the size the sensor serie chosen was A: 20mm diameter, the industry standard size for portable gas detectors. According to the operating range the model selected was E: high concentration.

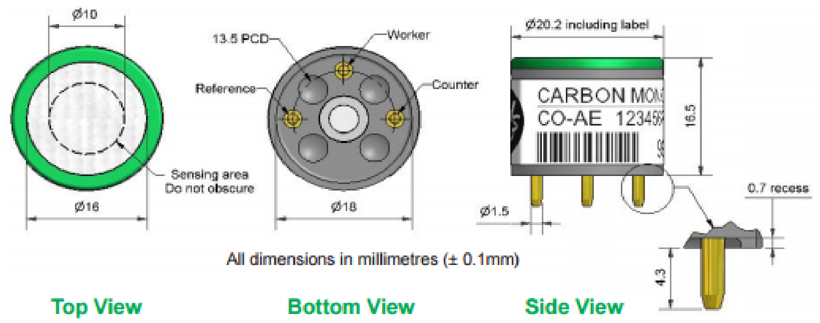


Figure 3.4: CO-AE Schematic Diagram [16]

As we can see in Fig. 3.4 and Fig. 3.5, the sensor is composed by three electrodes, **working**, **reference** and **counter** electrode. All these three electrodes are stacked parallel to each other.

The toxic gas sensors from Alphasense are electrochemical. Above in Fig. 3.5, the method how these work is represented.

These type of sensors are electrochemical cells that generate a current that is linearly proportional to the fractional volume of the gas [16].

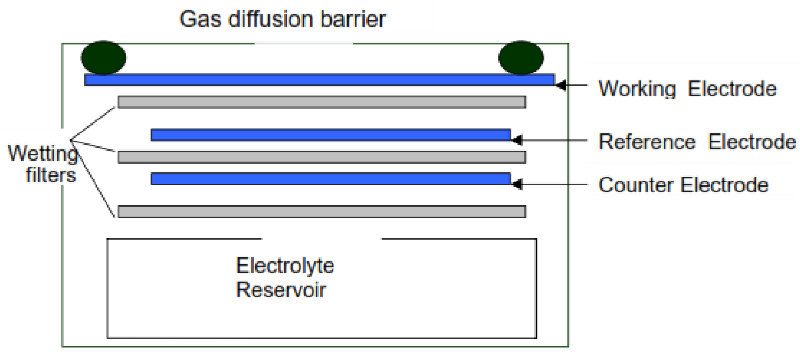


Figure 3.5: Schematic diagram of electrochemical toxic gas sensor [16]

The working electrode (WE) oxidises or reduces the respective gas. In addition, the counter electrode (CE) balances this reaction, i.e., if the working electrode oxidises a gas, then, the counter electrode has to reduce other molecule in order to maintain an equivalent current.

The potentiostatic circuit maintains the potential difference between the working and the reference electrode (RE) constant. Unlike the working electrode, the potential of the counter electrode does not need to be fixed, having the possibility to vary.

In clean air, the potential in the counter and working electrode is almost the same. Nevertheless, since the potential increases with the required current from the counter electrode, the potentiostatic circuit has to ensure an adequate current, so the counter electrode can operate at its favored potential [16].

Finally, the third element, the reference electrode forces the working electrode potential to a certain value ensuring it is always in the correct region of current-voltage curve -the flat zone represented in Fig. 3.6.

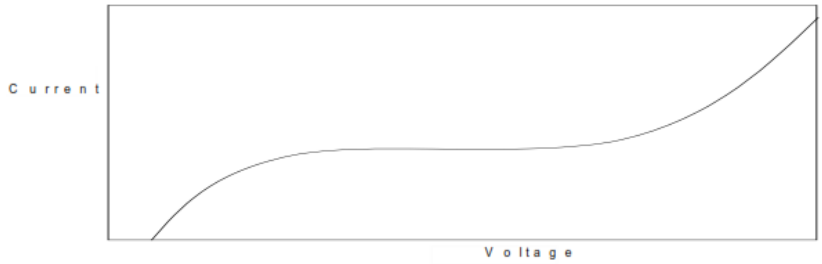


Figure 3.6: Schematic diagram of a typical current-voltage curve [16]

As we can notice, a variation in the potential induce also a variation in working electrode current. Still, in the flat region the generated current is almost constant even increasing the voltage.

Working in this zone give rise to "constant sensitivity, good linearity and minimum sensitivity to interfering gases" [16]. Thus, electrochemical toxic gas sensors are designed to work in this region.

In the Fig. 3.7 the simplest gas model is represented. Since the three electrodes are stack in parallel through the electrolyte, a common node is necessary. This can be modelled simply as a resistor, R_E. Once the potentiostatic circuit has a high input impedance to the reference electrode, carries no current hence there is no equivalent circuit.

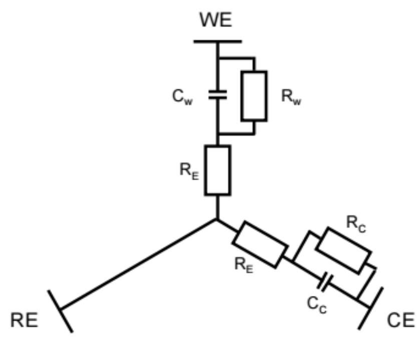


Figure 3.7: Gas sensor model [16]

Keeping in mind that a resistor describes the ohmic resistance correlated to the electrodes (best sensor means a lower resistor) and a capacitance is a relation between the quantity of charge accumulated by the body and the potential generated, the working and counter electrode can be modelled as a combination of resistors and capacitance as shown in the previous figure. Thus, and as the name indicated, R_w and R_c are the charge transfer resistance of working and counter electrode, respectively. Likewise, C_w and C_c are the working and counter electrode, respectively.

As this model is very simplified some considerations must be kept in mind such as: capacitance is frequency dependent and it is also a complex function of bias potential. Other important problem to be aware is if the sensor is used in low humidity ambient, there is a loss of electrolyte which leads to an increase of resistor, changing the constant time RC. Thus, the noise immunity is decreased and the system stability can be compromised.

3.2.2 Potentiostatic Circuit

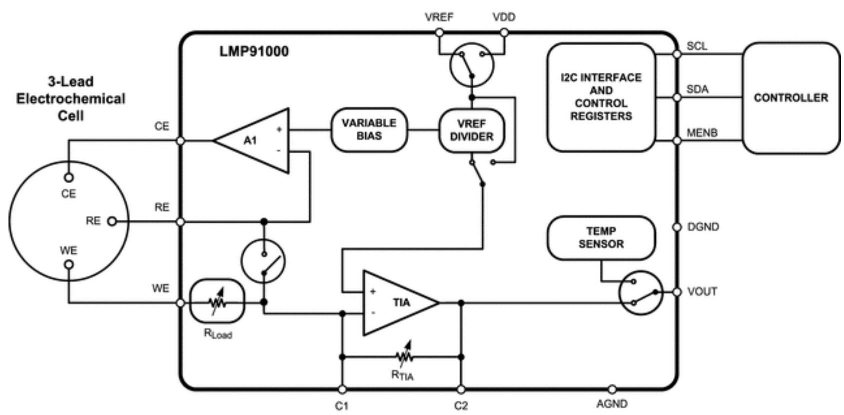


Figure 3.8: LMP91000 AFE Gas Detector [21]

LMP91000 is a "programmable analog front-end (AFE) for use in micro-power electrochemical sensing" [21] and is programmed through I2C.

This component provides a signal path solution between the sensor and the microcontroller and converts the cell current into a proportional voltage.

Design a sensor signal path needs a lot of time and effort. Typically, engineers takes weeks or even months to design a potentiostatic circuit since it is necessary to design, built, test and write a system algorithms [22].

Using the LMP from *Texas Instruments* is an easy-to-use solution once this integrated circuit allow the designers spend less time in the hardware development and dedicate more time to their own product firmware.

An LMP set by a lot of components since it is an integrated circuit which represented a correspondent complex circuit. Other advantage of LMP is its low power consumption, having a current consumption less than 10μA.

Thus, this is an easier and faster way to develop a potentiostatic circuit.

With the aim of power saving the transimpedance amplifier can be turned off and instead a load impedance equivalent can be switched in [21].

In Fig. 3.8 the functional block diagram is shown. This potentiostatic circuit compares the potential between required bias potential (set by variable bias circuitry) and the reference and working electrodes (see Control Amplifier - A1). The error signal is amplified through A1 and applied to the counter electrode.

A variation in impedance between WE and RE leads to a variation in the voltage applied to the counter in order to keep constant the voltage between WE and RE.

The transimpedance has the function of generate an output voltage that is proportional to the cell current.

Ultimately, potentiostatic compares RE voltage to the preferred bias potential. The voltage at counter electrode is adjust to maintain the ideal working-to-reference voltage [21].

3.2.3 ADC

An *analog-to-digital converter*, an electronic device which converts a continuous physical signal into a discrete signal , representing the signal amplitude in that moment. This is essential as it provides the data to be received and used by the microcontroller.

To implement an ADC, it is necessary to sample the data and quantify it, as shown in Fig. 3.9. This process also known as sampling is followed by quantization, i.e., process of constrain a set of continuous values into a finite set of discrete ones. Each of these values are called quantization levels. As we can easily understand, since we only take some values of continous signal there is a difference between analog value and the quantized digital value, this is called quantization error.

The discretized sample signals is represented, electronically, in binary form, or in other words, using bits.

The PIC chosen has an Internal Oscillator (F_{OSC}) of $8MHz$. Since the battery's consumption is proportional to the frequency, using low frequencies is mandatory, once our target audience are

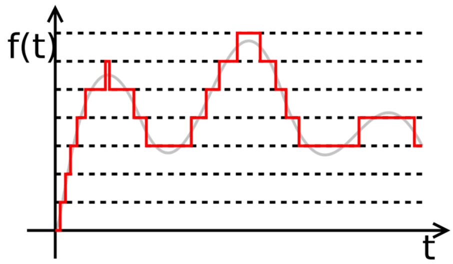


Figure 3.9: Analog & Digital Converter [23]

the firefighters and they spend several hours facing a fire. Keeping this in mind, we did not use the Phase Lock Loop (PLL) to multiply the frequency. The Processor Clock Source (F_{cy}) is divided by two, having so $4MHz$. The Instruction Cycle Period (T_{cy}) is $1 \setminus F_{OSC}$ or $1 \setminus 2 \cdot F_{OSC}$. As A/D Conversion Clock Select bits (ADCS register) we set it as $127 \cdot T_{cy}$. Thus, our sampling rate is $32kHz$.

An important characteristic of an ADC is its resolution. This means the number of bits which are used to represented the signal in the sample. So, the biggest the number of bits used, n, the lower the error.

Usually, the resolution is given in volts. Voltage resolution is the relation between the overall voltage measurement range and the number of discrete values.

ADC Voltage resolution, $$Q = \frac{V_{high} - V_{low}}{N} = \frac{V_{high} - V_{low}}{2^n}, \text{ N is the ADC bit resolution and n the number of bits.} \quad (3.1)$$

Considering this, the ideal situation is having the same ADC resolution as sensor resolution, at least as much as possible, to minimize the error.

For example, considering the CO case.

Table 3.2: CO-AE Technical Specification [24]

	Sensitivity	nA/ppm in 2,000ppm CO	10 to 25
	Response time	t90 (s) from zero to 2,000ppm CO	< 50
	Zero current	ppm equivalent in zero air	$< \pm 20$
PERFORMANCE	Resolution	RMS noise (ppm equivalent)	< 5
	Range	ppm CO limit of performance warranty	10,000
	Linearity	ppm error at full scale, linear at zero and 2000ppm CO	< 0 to 500
	Overgas limit	maximum ppm for stable response to gas pulse	100,000

$$2^n - 1 = 10000 \Rightarrow n = 14 \quad bits \quad (3.2)$$

As we will use an microcontroller with an 10-Bit ADC (see next subchapter), in order to get better results an external ADC should be used.

In the NO2 case, since its full scale is only about 200 ppm and ADC of 10-Bits is enough so the intern analog to digital converter can be used.

$$2^n - 1 = 200 \Rightarrow n = 8 \quad bits \tag{3.3}$$

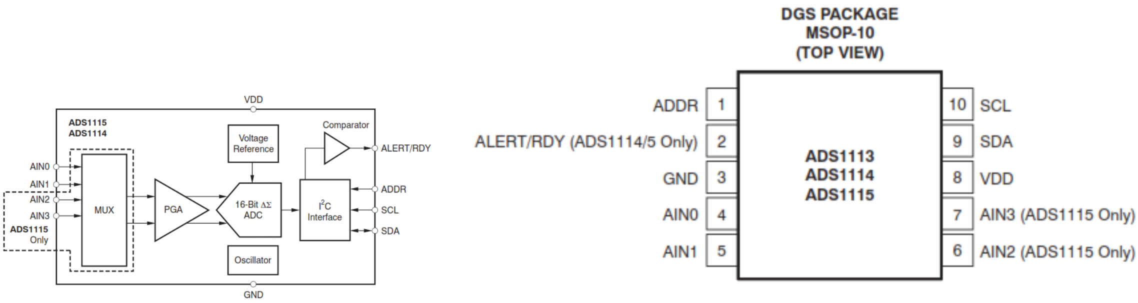
Note: The same procedure was realized for the rest of gas sensors.

To perform the analog-to-digital conversion of the slave sensor reads, a Texas Instruments ADS1115 Analog-to-Digital Converter (ADC) was used. This has a 16-bits of resolution and small size.

It stands between -40 and 125 °C C without losing efficiency, optimized for expected fire temperatures.

This external ADC can be configured through I2C. These types of ADC were designed with precision.

This module offers a single-shot mode (one conversion and automatic power down), although requires a low current consumption ($150\mu A$) in continuous mode, has a conversion rate up to 860 samples per second and offers large input ranges (+- 256 mV) allowing the processing of both large and small signals.



(a) Circuit equivalent

(b) Pin Configuration

Figure 3.10: ADS1114/1115 [25]

In Fig. 3.10a the equivalent circuit is represented. As we told before, the PGA offers a high resolution, accepting both large as small signals to be measured. On the other hand, the MUX provides two differential or four single-ended inputs.

Table 3.3: Comparation between ADS1114 and ADS1115 [25]

Device	Resolution (bits)	Maximum Sample Rate (SPS)	Comparator	PGA	Input Channels (Differential/Single-Ended)
ADS1114	16	860	yes	no	1/1
ADS1115	16	860	yes	no	2/4

In Fig. 3.10b and Table 3.3 we can compare the ADS1114 and ADS1115 devices. As we noticed, they are quite similar.

The ADS1115 is a two-channel module, i.e. allows two analog-to-digital conversions at the same time. However, only a single channel is used for each slave sensor, meaning that it could be an overkill solution to the problem at hand. In fact, its single-channel counterpart, ADS1114, was the selected module at the first time. However, ADS1115 is widely used in our laboratory, was available and has the same dimensions and price as ADS1114. Because of this, and looking forward to a future incorporation of new and parallel conversions using this same module that will be already implemented, we decided to use ADS1115.

3.2.4 Microcontroller

The microcontroller plays a pivotal role in data acquisition, processing and storage stages.

It contains a processor, memory and input/output peripherals and can be programmed for specific functions.

For our application, minimum requirements were established: (a) 3.3 V power supply; (b) serial and 2-channel I2C communication; (c) at least one ADC channel; (d) minimum of 14 pins.

We have selected the Microchip PIC24F64GA004 Microcontroller. It comprises 44 pins, 64k of programming memory, 8kb of SRAM, 13 ADC channels, 2 I2C channels and 2 UART channels. It is available in a reduced size QFN package, allowing its implementation into a more ergonomic helmet solution. This is a very powerful microcontroller, with several characteristics optimized.

In Fig. 3.11, the PIC24FJ64GA004's pin diagram is exposed.

Our slave sensors do not require such powerful solution and another, less powerful, PIC could be chosen. However, for logistical reasons (this microcontroller has ben used extensively in our group, the previously developed sensorization methods for the master board were programmed using this microcontroller and all the hardware is optimized for its communication) we decided to keep using this one. Additionally, Microchip microcontrollers are renowned and code samples are easily accessible for developers.

Microchip offers an application on its website [27] that allow the costumer to choose the microcontrollers can be ued through the necessary features.

Just as example the PICFJ16GA002, with 28 I/O pins, 16KB of Program Memory, 4KB of RAM and 2 I2C channel, it would be enough.

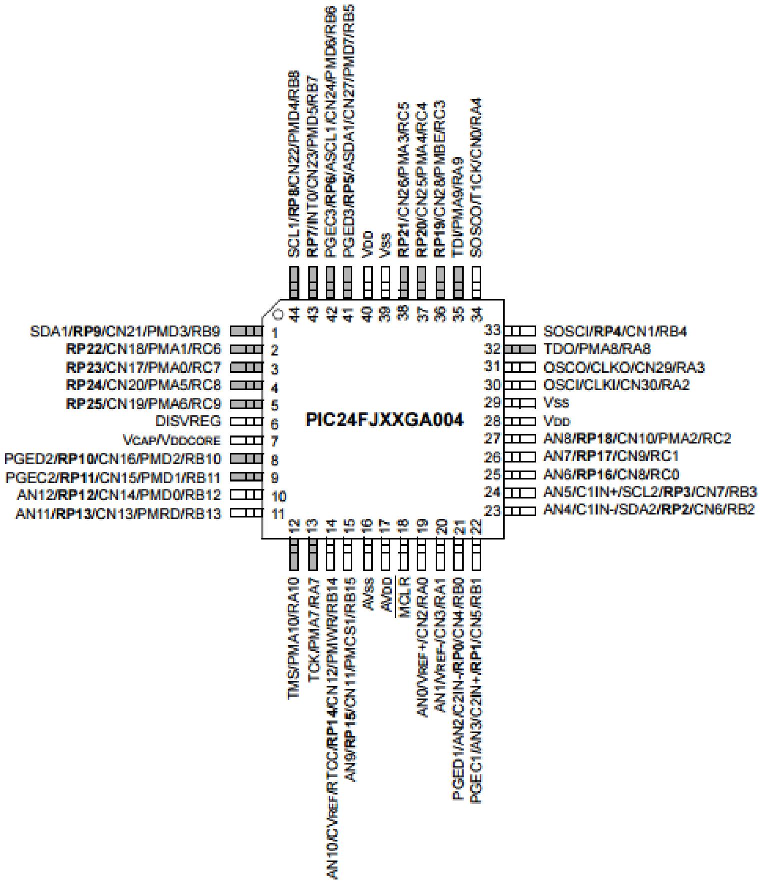


Figure 3.11: Pin Diagrams of a 44-Pin QFN [26]

3.3 Formfactor

The formfactor [1] of this project was designed and conducted to ensure the maximum comfort to the firefighter. At first, it has been thought of using this solution in one of the firefighters' uniform pocket as it actually happens in recent solutions (presented in Chapter 2). However, that would not be practical to the firefighter once he/she has to walk through the forest and bypass trees and bushes. Placing this solution on the belt would not be acceptable because it could hang on the hose or even in bushes. As so, it was decided to place this solution inside the helmet. It was thought to make the most of the space inside of the helmet, as represented in Fig. 3.12a, but soon we reached the conclusion that this would not be reliable because the sensors would not be exposed to gases which would harm measurements and consequently harm reliability of the data. Finally, aiming to get round all these problems, it has been decided to use the clip where the firefighter keeps the flashlight and put there our solution. This way we had to include a torch in our system, as shown in Fig. 3.12b and Fig. 3.12c. The AUTOCAD design view of flashlight solution can be observed in Fig. 3.13.

[1] "Form factor is a specification of physical dimensions, layouts, and other explicit information that helps ensure the hardware works with products that support that form factor. Form factors help prevent incompatibilities between multiple hardware manufacturers" [28].

(a) Space Inside of the Helmet (b) Front view (c) Top view

Figure 3.12: Position of Vital Helmet

This project had a lot of design criteria, such as a) Adaptable to the Helmet, b) Compatible with a flashlight and a camera, c) Lightweight and d) Tolerate collision, high temperatures and water. So having these criteria established we desired to create our product with the flashlight's shape and for its predefined location. However, and for the first assays, as it was impossible to find a pre-manufactured box we changed the *Vital Helmet* shape to a more rectangular one.

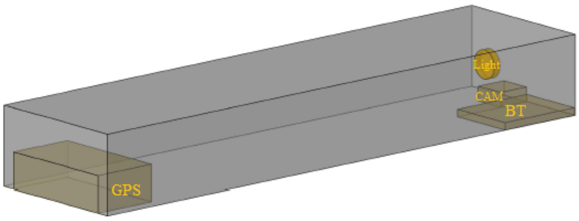


Figure 3.13: AUTOCAD design view

Chapter 4

Vital Helmet

This chapter addresses all the work done to implement the solution proposed in Chapter 3. First, some firmware issues as some pseudo-code and flowcharts will be explained. Then, we present the hardware design development as well as the tools used to do it. Finally, the type of communication selected for the VH will be described.

The software used to develop and implement firmware was *MPLAB X IDE* from *Microchip Technology* [29]. This software is an integrated development environment to program embedded applications on Microchip's microcontroller.

Our lab has established a standard programming and communication interface which uses an 8-pin socket (Fig. 4.1). This particular connector allows us to have power (VCC and GND), in-circuit programming (MCLR, PGC and PGD) and communications (Rx and Tx). To upload the firmware into our PCB, we also needed a debugger (*MPLAB ICD 3 In-Circuit Debugger*). To provide a connection between the debugger and the PCB a bootstrap programming board was developed by *Brain Team*. Other of the tools used for debuggng in the laboratory were *Tenma's* 72-9385 multimeter, an *Agilent Technologies'* DSO-X 2004A oscilloscope and a *Saleae Logic* data analyzer.

Top view

MCLR	RxD	PGC	GND
3.3V	PGD	TxD	NC

Figure 4.1: BRAINlab's 8-pin socket diagram

4.1 Data retrieval from gas sensors

4.1.1 Sensor and Potentiostatic Circuit

As a starting point of this dissertation, we begin by analyzing a first version of *Vital Helmet*, started by a *BRAIN team* developer. This version has its data format shown is Fig. 4.2.

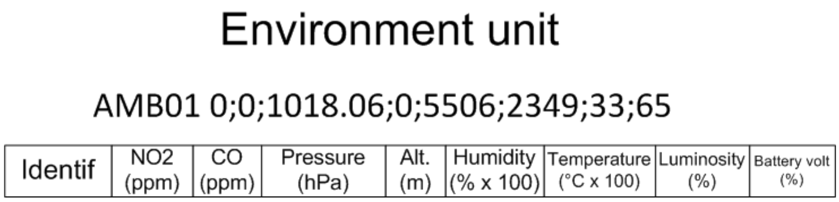
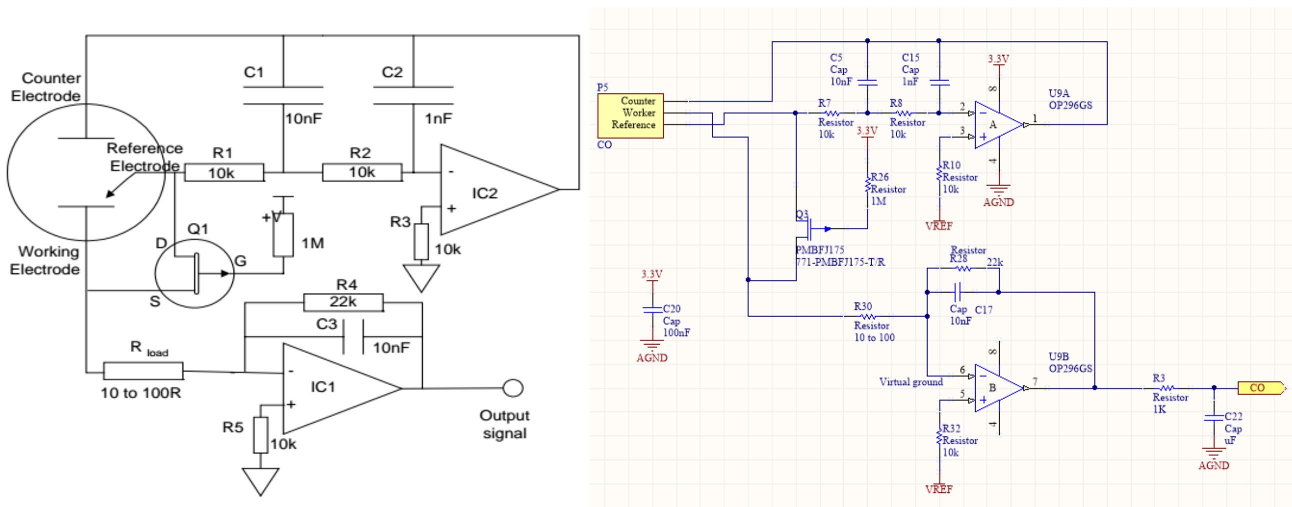


Figure 4.2: Data Streams Format of First Vital Helmet version

At this point of the project, the gas measurement was not implemented correctly. In Fig. 4.2 the data stream is represented. Starting with the sensor, and using a multimeter, its output was analyzed. By doing so we concluded that the sensor was working properly since there was a voltage output and blowing over the CO sensor the voltage measured increased, what makes sense since 4% of our expired air is CO. Thus, and after this, we validated the potentiostatic circuit. This was not working since it was impossible to detect voltage variations in its output. In this VH version the potentiostatic circuit was the one advised by *Alphasense* in their datasheets. The circuit and its implementation can be consulted in Fig. 4.3. One of the detected problems was in the amplifiers. Contrary to the datasheet suggestion, the control operational amplifier (IC) had a single ended power supply when the ICs require ± power supply.

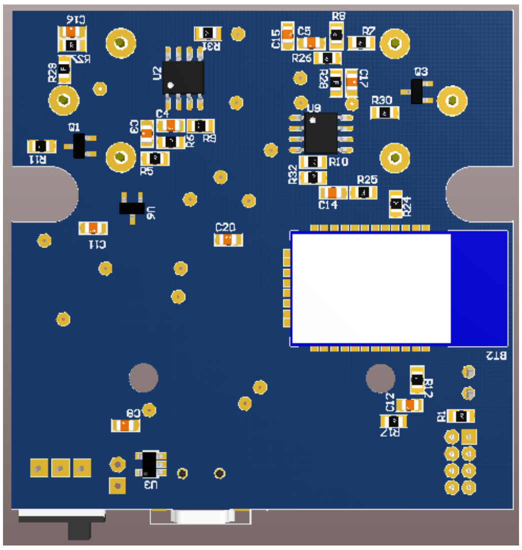


(a) Potentiostatic circuit advised by *Alphasense*[30] (b) Implemented potentiostatic circuit (*Altium* figure)

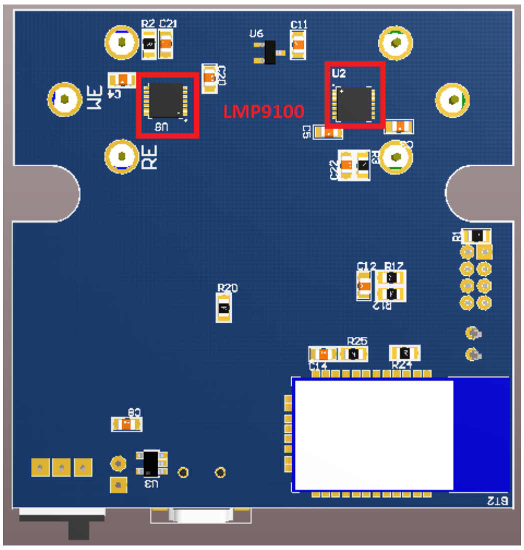
Figure 4.3: Potentiostatic circuit

In order to keep the circuit as simplest and smallest as possible we implemented the LMP91000 instead of this circuit and consequently improve the solution. As reported in the Section 3.2.2, LMP91000 is an easy-to-use solution to provide a signal path solution between the sensor and the PIC, converting the cell current into a proportional voltage. A new PCB was designed and soldered. Fig. 4.4a and Fig. 4.4b shows the difference between both implementations. As we noticed, the circuit where the LMP91000 was used is simpler than the first one. Even with the LMP91000 implemented, we could not yet retrieve the gas measurement . As there are a lot of bugs in the I^2C communication (these are listed in the silicon errata and will be discuss later in this dissertation) we decide to cut the I^2C vias, as it is shown in Fig. 4.4c. I^2C is only used to configure this device, so cutting the vias was not a problem since we only use the default configurations of potentiostatic circuit.

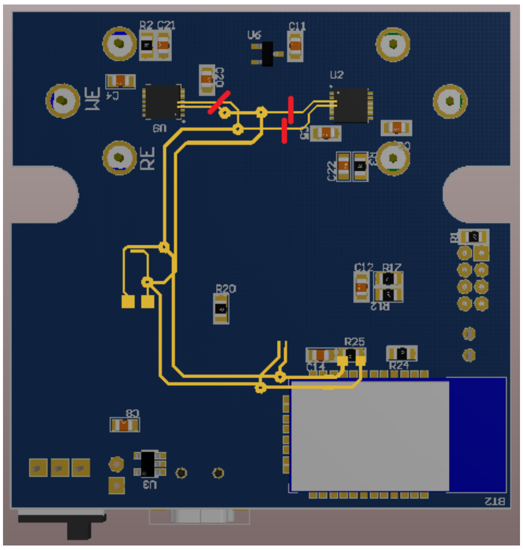
This action along with a correct filter was enough to have voltage at LMP output. The filter used was available from *Texas Instrument* [31].



(a) using the circuit advised by *Alphasense*



(b) using LMP91000



(c) Testing potentiostatic circuit problems

Figure 4.4: 3-D Schematic of potentiostatic circuit

4.1.2 ADC

Having the sensor and LMP working, an ADC function was programmed in order to read the gas output. The PIC24FJ64GA004, chosen for this project, has a 10-bit A/D Converter. This can have up to 13 analog input pins and 2 external voltage reference input pins.

Before we start programming an ADC function, we need to set up the registers. There are 4 types of registers: a) Control registers (ADC1CON1 and ADC1CON2), b) Input select registers (ADC1CHS), c) Port Configuration registers (AD1PFG) and, finally, d) Input scan selector registers. Thus, we create a function called *init_ADC* to initialize the registers and a function called *readADC* to sampling and hold the signal and store the value in a buffer, ADC1BUF0. In the Algorithm 4.1 these two functions are demonstrated. The first, *ADCinit* is quite simple but essential to the proper ADC's operation. In this function, some registers must be defined, according to the user's specification. Then, *readADC*, receives the channel as a parameter and start the sample and hold function. The data is stored in the ADC data buffer.

Algorithm 4.1 ADC [32]

```
function ADC_init(void)
   Select the port pins as analog inputs AD1PCFGbits.PCFGx =0
   Select the voltage reference source: AVDD and AVSS inputs are tied to VDD and VSS
   Select the analog conversion clock
   Select the appropriate sample/conversion sequence
   Select how conversion results are presented in the buffer
   Select the interrupt rate
   Turn on the A/D module
end function
function READADC(unsigned char chan)
   Set the channel, using the CHOSA register
   Sampling
   5ms delay
   Holding
     while A/D conversion is NOT done do Do nothing, just wait
     end while
return ADC1BUF0
end function
```

4.1.3 Permissible Exposure Limit

The permissible exposure limit is the maximum gas concentration to which a human being is allowed to be exposed to without danger. Since the contact with toxic gases occurs cumulatively, we perform the integration of the measures in a 15-minute and 8-hour time period. For that, we used the trapezoid rule for integration. It is the simplest integration strategy, although exhibiting an acceptable error range (it is not the module that generates the highest errors).

Integrating a signal is calculating the area under the function's curve, and according to the trapezoidal rule, an approximated result is obtained by dividing the region into small segments of the same width.

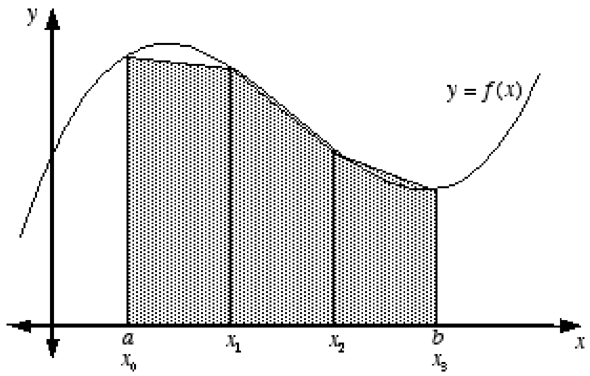


Figure 4.5: Trapezium rule [33]

As we can see in Fig. 4.5, if we approximate each segment of the function's curve as a straight line, the area of each segment comes as a trapezoid.

Since the area of a trapezoid is:

$$A = \frac{(B+b)\cdot h}{2} \text{, where B and b are the parallel sides and h is the height,} \tag{4.1}$$

the area of the n-segment is:

$$A_n = (x_n - x_{n-1}) \cdot \frac{y_n + y_{n+1}}{2} \tag{4.2}$$

Thus, the area under the curve is $\sum_n A_n$, i.e,

$$A \simeq \frac{\triangle x}{2} \cdot \left(f(a) + f(x_1) + 2\sum_{i=2}^{n} f(x_i) \right) \tag{4.3}$$

The gas concentration values obtained through this trapezium rule are then used for periodically checking if the permissible exposure limits were not exceeded. There are 3 types of permissible exposure limits, as explained in the Chapter 2 Existing Market Solutions: CEILING sets the limit for the maximum permissible value of a gas concentration at a given instant; STEL for the average gas concentration over a period of 15 minutes; and TWA for a period of 8 hours. Algorithm 4.2 shows how the control of the PEL was implemented. As we can see in case any of these thresholds be exceeded an alarm signal must be sent to the master.

Algorithm 4.2 Permissible Exposure Limit

```
while 1 do
    Reset exposition_time.hours
    a = READADC(chan)
    while exposition_time.hours < 8 do
        while exposition_time.minutes < 15 do
            A = READADC(chan)
            if A > CEILING then
                Send an alarm signal to master
            end if
            Integrate signal between a and A, i.e., trapezium rule
            Update mean gas concentration
            if mean gas concentration > STEL then
                Send an alarm signal to master
            end if
            a = A and A = 0
        end while
        Reset exposition_time.minutes
    end while
    if mean gas concentration > TWA then
        Send an alarm signal to master
    end if
end while
```

4.2 Conversion of Output Current to ppm

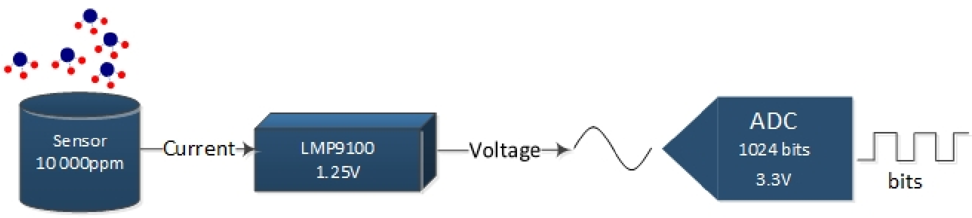


Figure 4.6: Diagram of output current conversion to ppm

The conversion of output current to ppm is depicted in Fig. 4.6. As seen in this figure, the sensor output is current, then, the LMP91000 output is voltage and finally ADC output is digital-converted values (10 bits). So, as we are measuring gas concentration we want the output express in ppm. If we define adc_{value} as the ADC output, Vref, the voltage supply, and N, the number of bits, then ADC voltage is:

$$voltage\_adc = \frac{adc\_value \cdot Vref}{N} \tag{4.4}$$

Afterwards, and keeping the same line of thought, the LMP output is:

$$voltage\_lmp = \frac{voltage\_adc \cdot Vref\_lmp}{Vref} = \frac{adc\_value \cdot Vref \cdot Vref\_lmp}{N \cdot Vref}$$

$$= \frac{adc\_value \cdot Vref\_lmp}{N},$$

where Vref_Imp is the LMP references voltage and N is the ADC's resolution (4.5)

Finally, the gas concentration is:

$$gas(ppm) = \frac{voltage\_lmp \cdot FS}{Vref\_lmp} = \frac{Vref\_lmp \cdot adc\_value}{N \cdot Vref\_lmp} = \frac{adc\_value}{N}$$

, being FS the gas full scale (4.6)

4.3 Hardware Design

In this section we present the hardware design developed. After designed the slave and master PCBs, it was necessary to weld them and check the electric connectivity using a multimeter.

We chose a PCB thickness of 1.55mm to increased the rigidity and be stronger. Other important issue was the project of some through-holes where the uC would be soldered to dissipate heat.

4.3.1 Slave

In Fig. 4.7, the schematic of Slave PCB is described. As we saw in the previous chapter its main components are the microcontroller, the potentiostatic circuit and the external ADC.

This project was developed considering the need of a small size. We managed a size of only 2.4 x 2.85 cm.

In order to reduce the overall size, we projected a PCB using both sides, i.e., on one side we have just the sensor and on the other side, under the sensor, we have all the necessary electronic components.

Other decisions made to reduce the size of our PCBs was using I^2C instead of other type of communication because I^2C only uses two bidirectional open-drain lines, Serial Data Line (SDA) and Serial Clock Line (SCL). This will be further explained in Section 4.4.

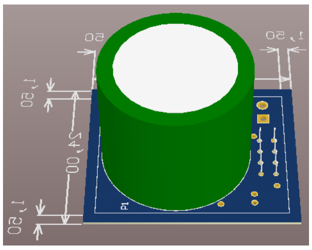
We also provide a BRAINLab's 8-pin socket in case I^2C does not work properly.

The average production cost is €75.

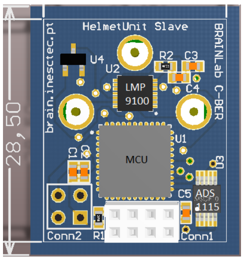
4.3.2 Master

Although slightly out of the scope of this thesis, we have also designed and soldered the master board in order to integrated our work in the rest of the system and thus, be able to conduct experiments in real operation scenarios.

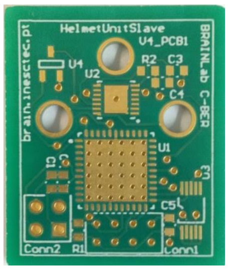
The *Master board* is a more complex unit, having several ambient sensors, bluetooth and GPS. While designing this PCB we already anticipate a camera and a flashlight.



(a) Front View



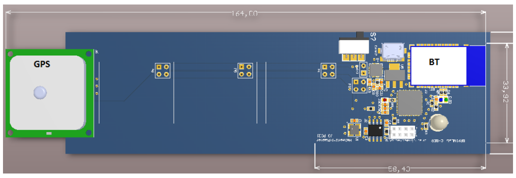
(b) Back View



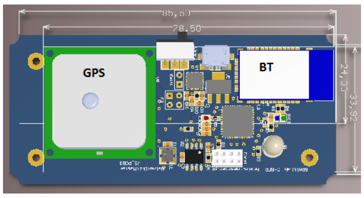
(c) PCB under production

Figure 4.7: 3-D Schematic of Slave PCB project and its production

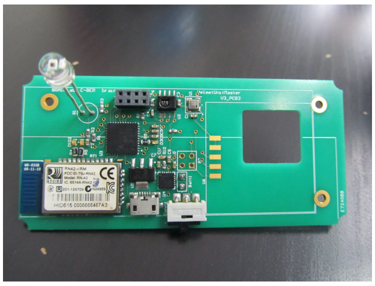
The master's PCB design has evolved accordingly to the evolution of the form factor. Thus, the first version was designed in a flashlight fashion, to allow its placement into the flashlight's clip. The lack of existent premanufactured boxes with the desired dimensions, motivated us to redesign the master board in order to be as small as possible and adaptable to a prefabricated box. Both implementations are represented in Fig. 4.8a and Fig. 4.8b. To achieve this goal of being a small solution we design a plate which purpose is to rearrange the sensors position into the master board as depicted in Fig. 4.10b. Fig. 4.8c shows the master board soldered and the 3-D Schematic of PCB plate can be seen in Fig. 4.9a.



(a) Flashlight solution



(b) Smaller version

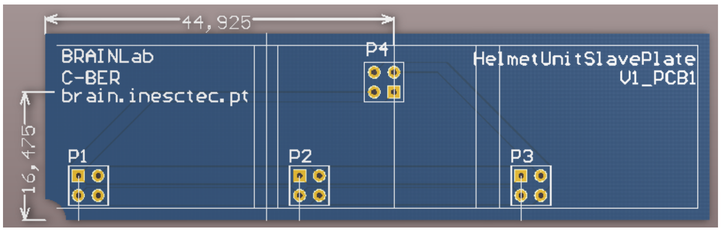


(c) Welded Master

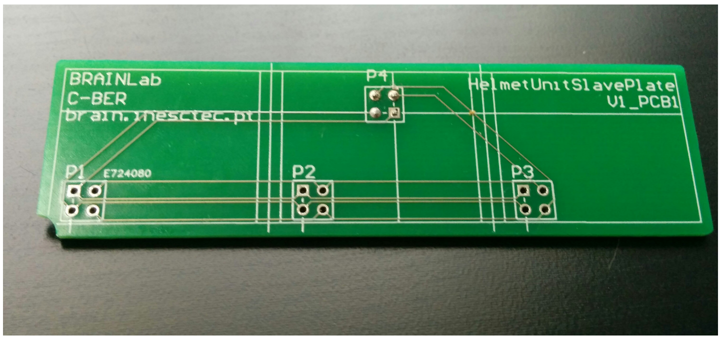
Figure 4.8: 3-D Schematic of Master PCB Project

The *PCB plate* is simply a mechanical plate which aims to connect the master and the slave.

Fig. 4.11 shows the enclosure selected to the *Vital Helmet*. The material box is Acrylonitrile Butadiene Styrene (ABS). The size of the box is 38mm x 104mm x 50mm. The biggest piece of our system is the master (approximately 85.50mm x 33.92mm x 40mm), thus, this box is a little bit bigger than the supposed. However, it was the closest match.

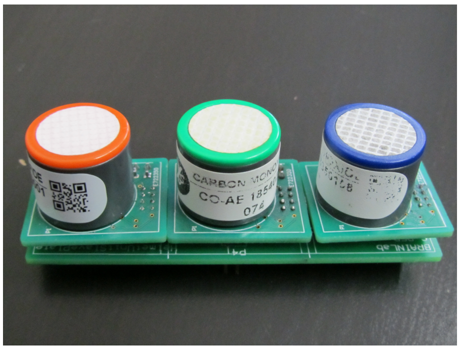


(a) 3-D Schematic of Plate PCB Project

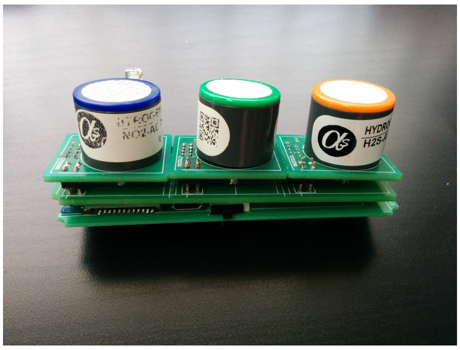


(b) Plate welded

Figure 4.9: Plate PCB



(a) Plate with 3 slaves on it



(b) Slave and Master connected through the plate

Figure 4.10: Welded PCBs

Figure 4.11: Vital Helmet Enclosure [34]

4.4 Communication

"I^2C is a serial protocol for two-wire interface to connect low-speed devices like microcontrollers, EEPROMs, A/D and D/A converters, I/O interfaces and other similar peripherals in embedded systems"[35].

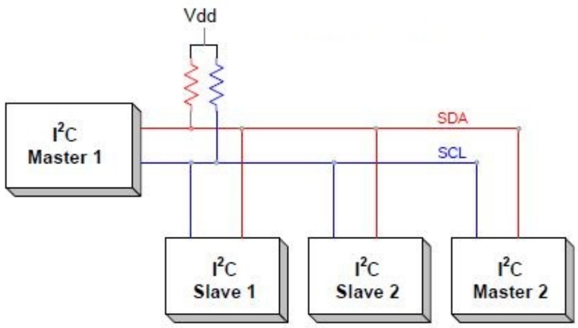


Figure 4.12: Typical I^2C Bus [36]

As previously mentioned, in I^2C protocol only two wires are required: a serial data line (SDA) and a serial clock line (SCL). This reason was one of the most important ones to choose this type of communication rather than any other. This protocol is quite common in a Master/Slave communication since each device connected to the bus has a unique address. Thus, it is possible to have several devices interconnected. Another issue to bear in mind is the fact masters are able to operate as receivers or transmitters which provide us greater communication versatility.

Some reasons why I^2C was chosen instead of others types of communication, such as UART or SPI, are presented in Table 4.1. As we can see, I^2C protocol leads this project to greater versatility and scalability.

Table 4.1: Pros and Cons of the different buses [37]

	I^2C	UART	SPI
Advantages	-Well know -Universally accepted -Plug&Plays -Large portfolio -Cost effective	-Well know -Cost effective -Simple	-Fast -Universally accepted -Low cost -Large portfolio
Disadvantages	-Limited Speed	-Limited functionality -Point to point	-No Plug&Play -No "fixed" standard

The main idea, in using this protocol, was having several slaves sending data and a single master receiving it. Thus, it was necessary to program a **slave sender** and a **master receiver** routine.

The Fig. 4.13 shows the master read flowchart. First of all, the I^2C communication must be opened (with I2CON and I2CBRG set) and only the Master can initiate a communication. To do that, the master sends a start condition (S). In this situation, the SCL line is high, however, the

SDA line suffers a high to low transition. Then, a wait condition is generated until I2C bus is Idle. Posteriorly, master sends to the line the 7-bit slave address with the 8th bit as write condition, i.e, the last bit is low. After, sending a star condition again, it sends the slave address with the last bit high, i.e, as a reading state. Each slave will be on standby, and checking if the slave address sent corresponds to its own. And if so, the slave sends acknowledge condition(ACK) to the master. Finally, master reads as many data bytes desired and terminates the transaction with a stop sequence. An Idle state is created. On the slave side, represented in Fig. 4.14, the slave is always verifying the address sent by the master. In case of a match to its own, the slave device writes the data to the I^2C line.

In an effort to enhance my self-learning, the decision of program the I^2C from the very beginning was made. This decision was also encouraged by the fact that the existing code in the lab does not follow the rules of the datasheet, as an example, the lab code treated all sensors as masters devices. To program this protocol we used a development board, the *Explorer 16 Development Board* from *Microchip* and the microcontroller board *Arduino UNO R3* [1]. According to *Vital Helmet* system the slave measures the gas concentration and sends the data to the master which has to read it. Hence, being a master means reading data and being a slave means writing data.

Fig. 4.15, shows our first experience where we set up the *Explorer 16* as a master and the *Arduino* as a slave. To analyze the results, a logic analyzer software was adopted, the *Logic* from *Saleae* [2]. As we realize in Fig. 4.16, the master starts the communication (green signal) and writes the string *PI*. However, the slave always sends a not acknowledge (NACK). In case a master receives a NACK the data must be resent, and as we see, this did not happen here. At the beginning, we did not give much importance to this result since we thought that was motivated by synchronization problems between different devices.

The next experience was the opposite, we set up the development boards as slave and the Arduino as Master and the result was that represented in Fig. 4.17.In this case, although the slave had sent an ACK, the master was unable to read the data sent.

Following, and trying to correct these problems, we try the same experiments with two development boards. However, results were the same.

The next step was to repeat these 3 experiments but using the functions given by *Microchip*. Once again, there were not new and, specially, correct results. After some research on the Internet we concluded that there are several I^2C errata to this pic, as evidenced in the silicon errata [38] present in the Appendix A.3 of this dissertation. Every effort has been made to the success of this stage, from looking for help from FEUP's microcontrollers professor, prof. Paulo Gomes da Costa [3], asking for help to Biodevices' technical Vitor Sousa [4] up to going through online forums, such as *Microchip Forum* and *StackOverFlow*[5].

[1] https://www.arduino.cc/en/Main/arduinoBoardUno
[2] https://www.saleae.com/logic/
[3] https://sigarra.up.pt/feup/pt/func_geral.formview?p_codigo=211795
[4] https://pt.linkedin.com/pub/vitor-castro/100/42/5bb
[5] http://stackoverflow.com/

In order to speed up the PCB's tests, and due to the lack of time, I decided to continue using lab code despite its inconsistencies. This code is able to read sensors through I^2C but it is not able to send data between them using $I2C$. Since we were already counting on potential problems with I^2C communication, we projected our PCBs providing UART communication. Hence, we can send the data via a serial port and analyze them on PC.

By the time this paper was being concluded,, we are trying to fix this problem using the $MPLAB$®$CodeConfigurator$[6] from *Microchip*.

[6] http://www.microchip.com/pagehandler/en_us/devtools/code_configurator/home.html

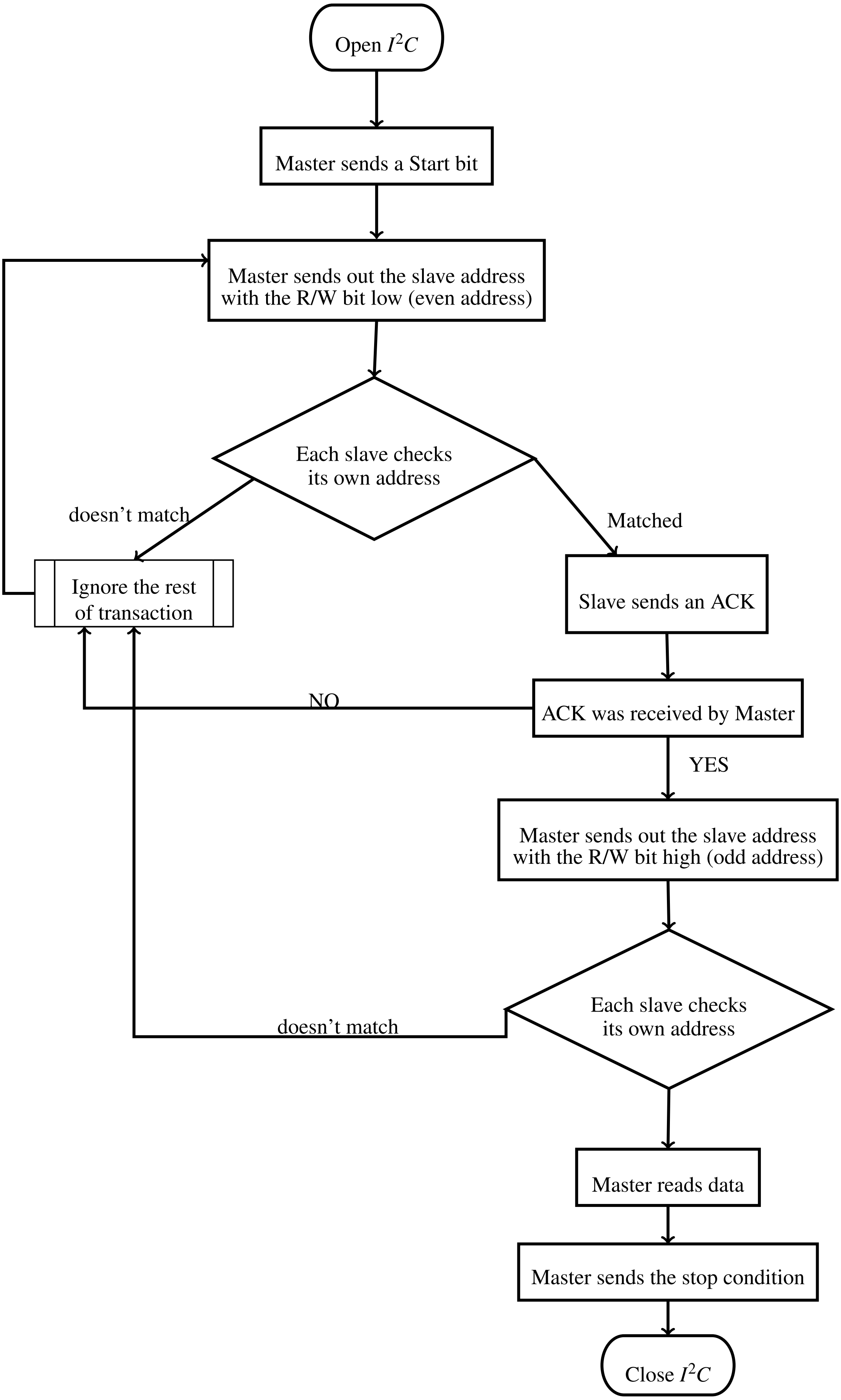


Figure 4.13: Flowchart of Master routine

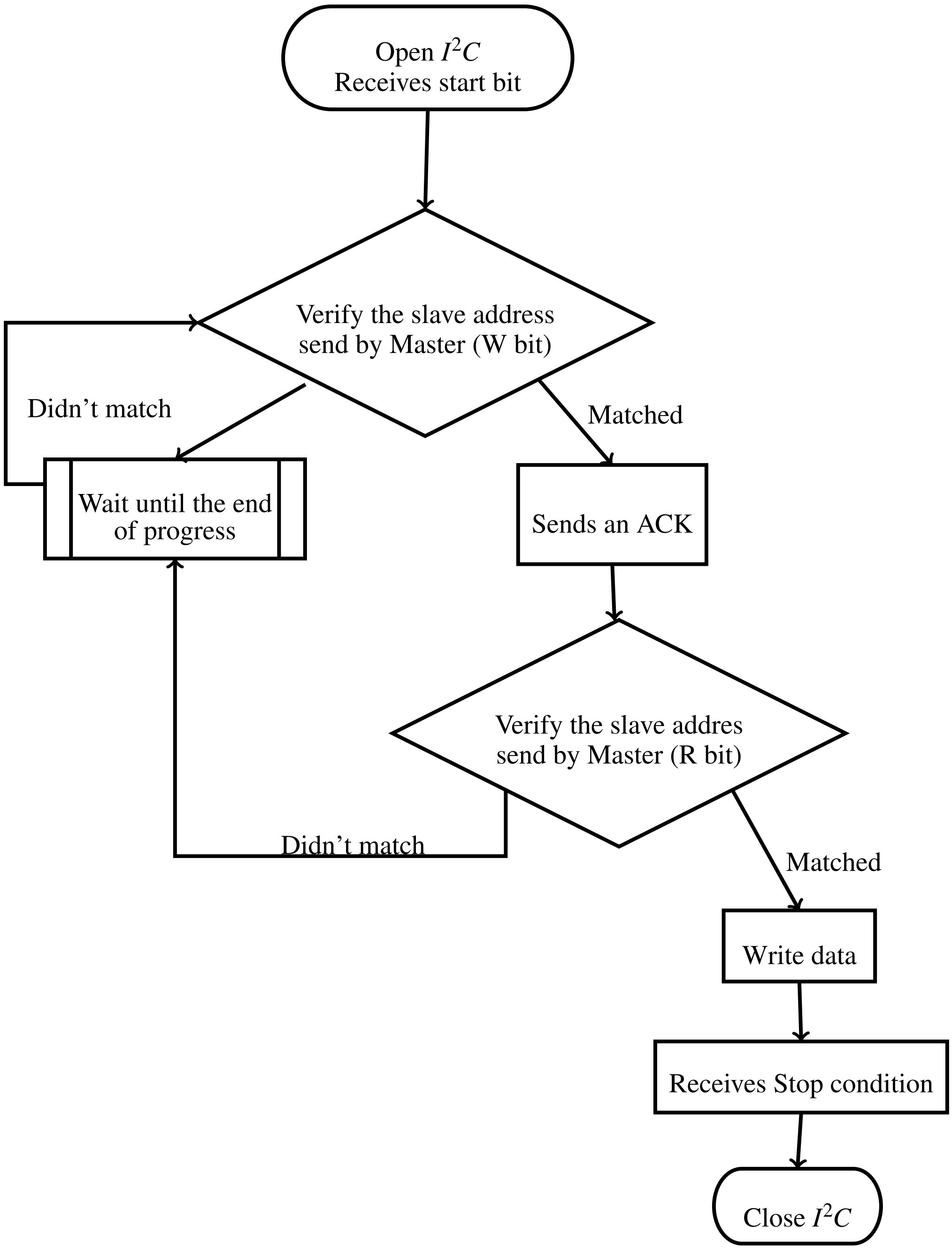


Figure 4.14: Flowchart of Slave routine

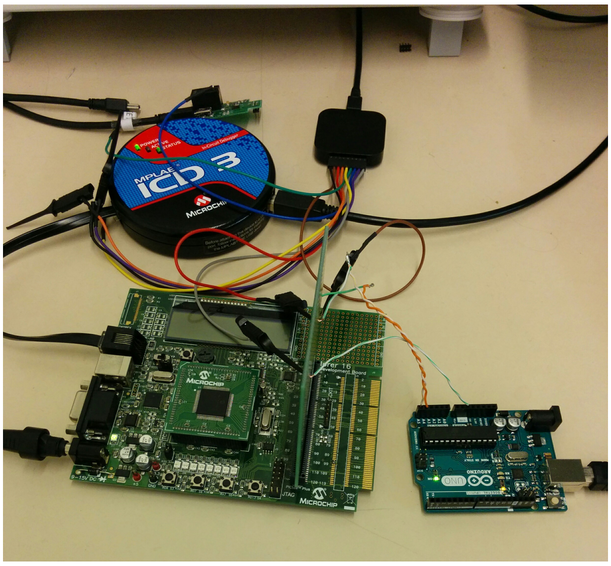


Figure 4.15: Testing I^2C communication using a Explorer 16 and a Arduino.

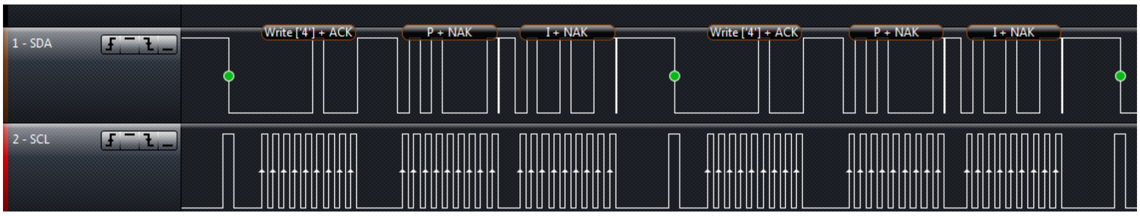


Figure 4.16: Testing I^2C communication using a Explorer 16 and an Arduino.

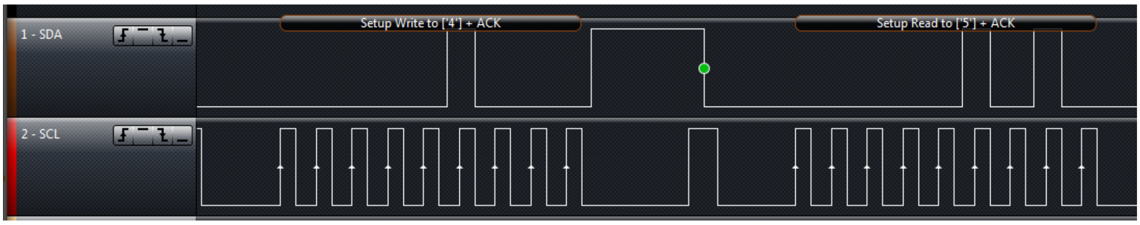


Figure 4.17: Testing I^2C communication using a Explorer 16 and an Arduino.

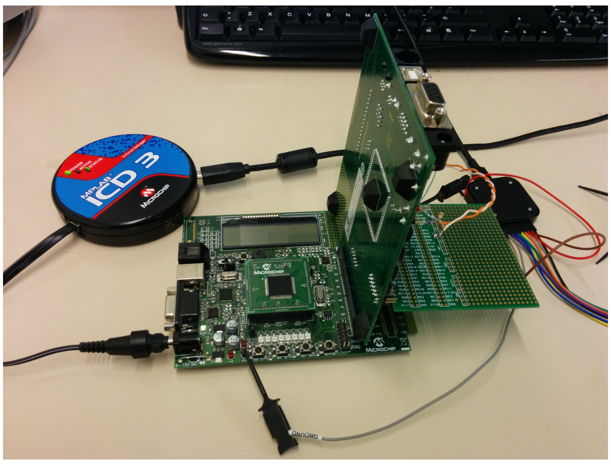


Figure 4.18: Testing I^2C using two development boards

Chapter 5

Testbed and Results

In this chapter we present and analyze the experimental results and some conclusions.

It is mandatory to point out that all the tests presented in this chapter were elaborated with non-calibrated sensors for reasons beyond our control, as exposed in Appendix A.4.

Due to this problem, the tests realized are quite simple although are enough to understand the behavior of our sensors and provide proof of concept. In order to analyze them, and because we were working with non-calibrated sensors, we normalized the measurements, thus, doing a qualitative analysis.

We would like to analyze our system in a real scenario such as a fire, however, this was not possible since, at the time of this dissertation, controlled fires are not allowed due to the forest fire seasons.

5.1 Experimental Tests

In this section we define the set up of experimental tests.

To collect data we resort to a serial communication. For that we used a *Universal Asynchronous Receiver/Transmitter (UART)*. We chose this type of communication to our tests since it is very simple and commonly used in microcontrollers. Basically, the UART receives bytes of data and transmits bits sequentially.

In terms of software, our choice was the *PComm Terminal Emulator*. [1] Thus, we were able to observe the results in real-time and capture it to a text file.

All the tests presented here were accomplished with a CO sensor, since CO is one of the most common gases and easily found in the environment.

We did 4 different tests. Although rudimentary, we were able to conclude that our sensor is working properly. In the first test, we enclosed a candle in a pot until the flame goes out. The idea was to prove that our sensor was responding to stimuli, being able to stabilize after it. The second experiment aimed to test the sensor's response exposing it to different scenarios, such as a

[1] http://www.moxa.com/product/download_pcommlite_info.htm

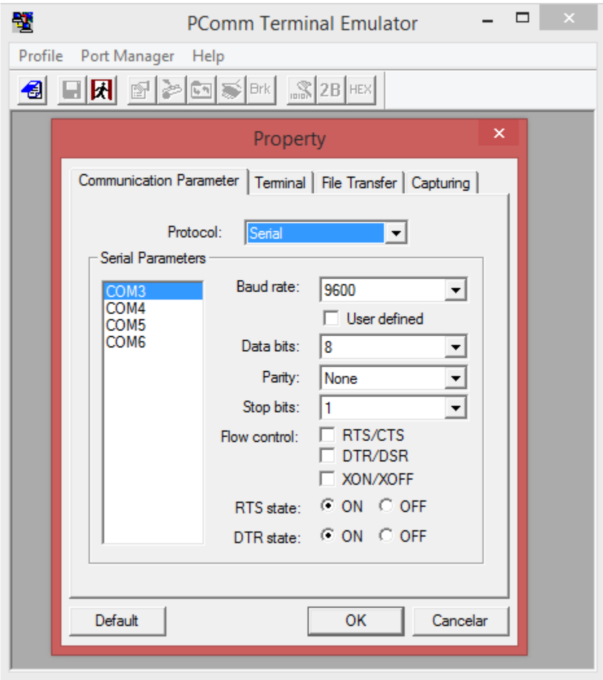


Figure 5.1: Pcomm Terminal Emulator

living room and a garage. Finally, we asked a smoker to blow upward at sensor and after that we evaluated the signal response comparing it with laying the sensor above the cigarette.

5.1.1 Enclosed Candle

As shown in Fig. 5.2, to accomplish this test a candle, a pot and phosphors were used. We compared our solution with the gas detector used by firefighters, in this case the MSA ALTAIR®4x.

Figure 5.2: Material to enclosed burning candle test

We enclosed a candle in a pot (approximately $253cm^2$ of volume) until the flame went out. As demonstrated in the Fig. 5.3, both devices increased the CO value linearly. When the combustion

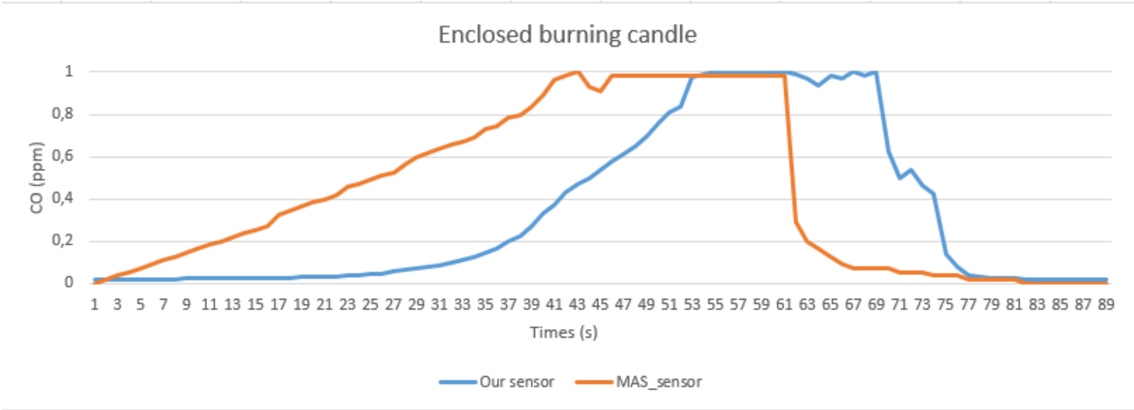


Figure 5.3: Exhaust CO by an enclosed candle

ended up, we waited a few seconds to analyze the sensor behavior. As expected, the CO values were kept constant. After that, we opened the lid and, as the O2 increased and the CO was not compressed anymore to a volume, this started to decrease until stabilized.

The disparity between the curves show the difference in the device time response. As we can confirm in Table 5.1, *MSA Altair 4x* has a faster response time than the *Vital Helmet*. Other important characteristic to observe is the time during which the gas concentration is kept constant. In either case, this time is approximately 16 seconds, corroborating with the sensor's proper functioning.

Table 5.1: Comparison of some important characteristic between Vital Helmet and MSA Altair 4x [39] [24]

	Vital Helmet	**MSA Altair 4x**
Resolution	<5ppm	1ppm
Range	10 000ppm	1999ppm
Response time	<50s	<15s

5.1.2 Indoor test

The indoor test helped us to visualize the sensor behavior when present at an exhaust pipe, as shown in Fig. 5.4. First, we were in the living room and we moved to the building corridor. We went down in the elevator until the garage. As expected, the CO level was increasing with the garage's approach. Furthermore, the higher CO level occurred when the sensor was placed in the exhaust pipe and the car sped up. These results are presented in Fig. 5.5.

Figure 5.4: Car exhaust gases

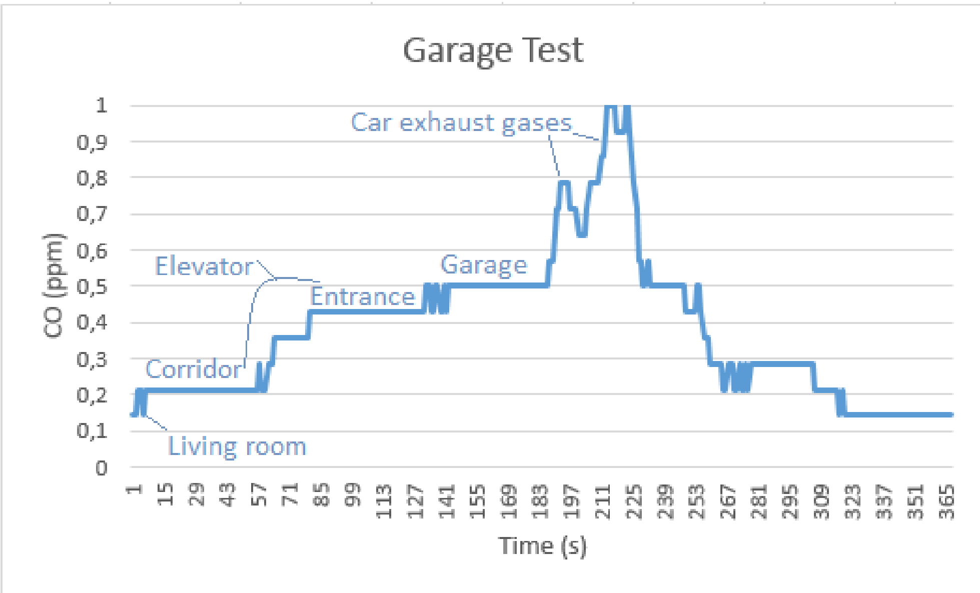


Figure 5.5: Car exhaust gases

5.1.3 Smoking

In this test we ask a smoker to blowing upward at sensor. Every time he did it, the sensor responded to the stimuli, stabilizing after that. To corroborate the proper functioning of the sensor, we located it above the cigarette for a few seconds, as explained in Fig. 5.6. As expected the CO value was constant during this phase. These results can be observe in Fig. 5.7.

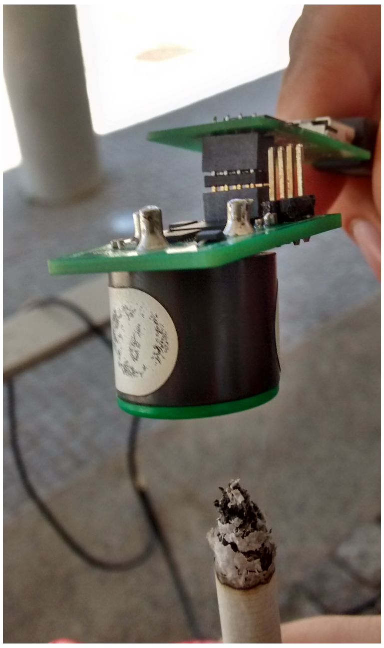


Figure 5.6: Smoking test

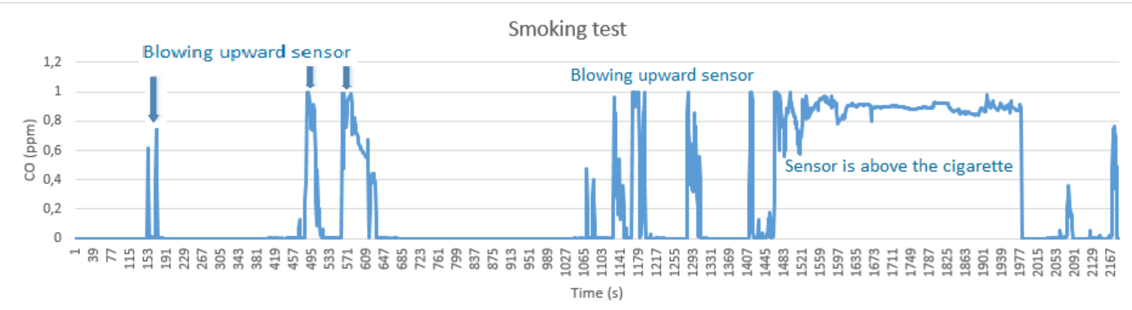


Figure 5.7: Blowing upward sensor

5.2 Calibration

To ensure sensor accuracy and system integrity, gas sensors need to be calibrated and periodically checked.

Despite being a bit outside the scope of this dissertation, we set out to calibrate the sensors in order to have the slave entirely ready to be received by the master.

As demonstrated in the e-mail sent to Post-Doctoral Joana Valente [2] and presented in Appendix A.4, the *Instituto Do Ambiente E Desenvolvimento - IDAD* were not able to calibrate at high gas levels. At this point, we are waiting to receive commercial sensors. At an early stage we will use the *Universidade de Aveiro*'s [3] sensors, which only work at low concentrations, for the calibration. Then, we will analyze the calibration curves and thus calibrate our system by comparison. This may not be simple since the sensor behavior is not linear. In a first stage, we will calibrate our sensors within the limits of IDAD's sensors.

At a later stage of the project, we will calibrate our sensors according to the manufacture advices, making it necessary to acquire high concentration gas bottles.

The manufacturer recommends a simple and straightforward calibration, and easily executed by regular personnel [40].

Calibration of the gas sensor occurs into two steps. First, the *"zero"* must be set and then the *span* must be calibrated.

It is really hard to define the zero air. The most correct method to **set the "zero" of the sensor** is using the air surrounding it when the area is clean. This reference point can be difficult to establish. Frequently, a good reference point can be in the area where air is always considered clean, such as in an office area, i.e, a controlled environment.

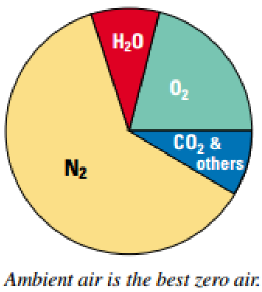


Figure 5.8: "Ambient air is the best zero air" [40]

Premixed gas mixtures, with previously known gas concentration, are compressed and stored under pressure in a gas bottle. Although available in many sizes, smaller, lightweight solutions are preferred. These small portable bottles are available in two different categories: a low-pressure and a high-pressure version. For calibration gases, these bottles are normally made of thick-walled

[2] http://www.cesam.ua.pt/index.php?tabela=pessoaldetail&menu=95&user=140
[3] http://www.ua.pt/dao/

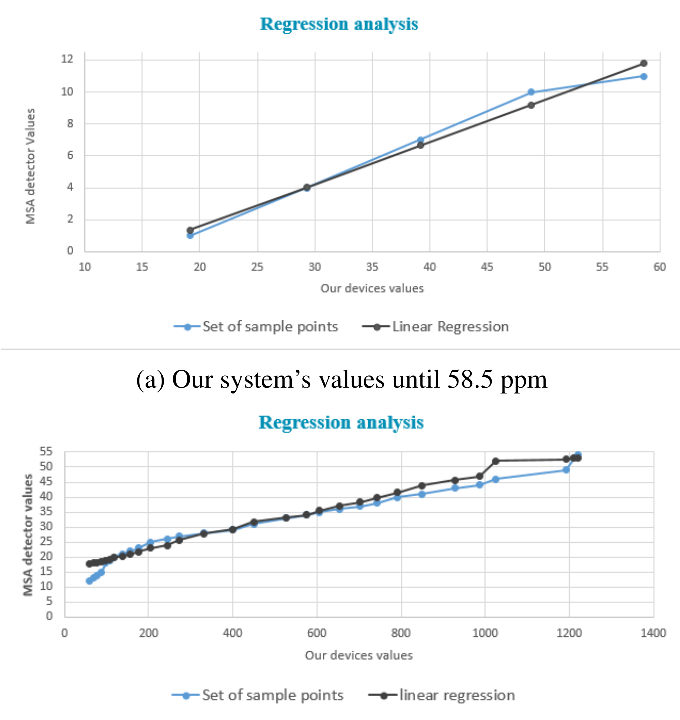
aluminium which has a service pressure of 2000 psi. When operating, the high-pressurized gas inside the bottle is ejected at a reduced pressure (only a few psi), allowing a continuous and constant air flow through the orifice. To do that a pressure regulator, a pressure gauge, and an orifice flow restrictor are needed. Commonly used flow rates vary between 600 and 1000 cc/min. Sensor voltage readings under each known concentration are used to fit the best model that can be used to measure gas concentration in the operating environment.

Figure 5.9: Calibration gas bottles [40]

5.2.1 Calibration by Comparison

Since it was not possible calibrated our device due to the lack of material, we did a calibration by comparison, i.e, we placed our sensor and a MSA Altair 4x into a pot with a burning candle and we registered both values. Then, we compared both cases and implemented a mathematical model. As can be seen in Fig. 5.3, our system's response is slower in the first 35s (as expected according to the sensor datasheet). After tried some mathematical models such as exponential one, we realized the model which introduced less error was the linear regression, considering the signal into two parts: a) first, when the system start to response slower and b) then, when the signal starts to response faster and goes in accordance to the MSA devices' signals.

For the first case, we came into the equation $y = 0.264279x - 3,7074$. In the second one, the equation which represented the linear regression between our solution and MSA device is $y = 0,030557x + 15.5879$. According to the correlation coefficient, we achieved 99% and 98%, respectively. Thus, at this moment, we have our system working as well as a marketed and legislated device, as shown in



(a) Our system's values until 58.5 ppm

(b) Our system's values from 58.5 ppm

Figure 5.10: Linear Regression Analysis

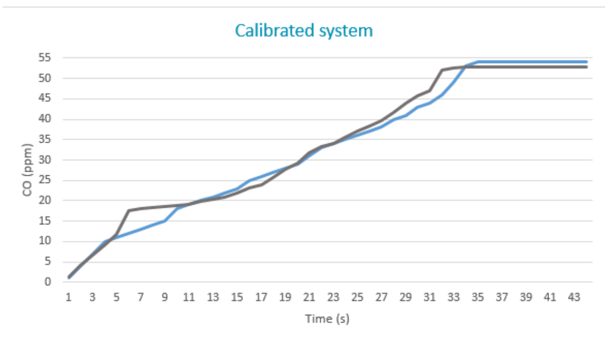


Figure 5.11: Results after calibration and its comparison with MSA device's results.

Chapter 6

Conclusions and FutureWork

Being a fireman means performing one of the most dangerous jobs in the world. Facing an operating theater (OT) of thick smoke, high flames and high temperatures can lead to many health problems and accidents. Thus, it is crucial to monitor the environmental conditions that firefighters undergo and our proposed solution -*Vital Helmet*- is essential to safeguard the lives of these professionals.

Most of the research in gas monitoring is based on heavy and unpractical devices. Furthermore, firemen have no option to choose which gases they want to monitor. As far we now, we propose a major novelty on the gas monitorization and to the best of our knowledge we are involved in the single one project that provide an adaptable solution to the emergency scenario.

In this MSc thesis we proposed the *Vital Helmet* project, an international project for the monitorization of firefighters in action. Moreover, we have submitted some tests to evaluate our hardware design as well as our solution. We successfully finished a prototype that measures gas concentrations from the surrounding environment and sends the data to a PC through UART. The solution is running without problems. However, it is still necessary to calibrate the sensors. We are now finishing, the I2C communication between each of the slaves and the master, whose implementation is much more complex. However, we are still working on it.

Our solution has great potential compared to other solutions and technologies because it is a new generation of personal gas detectors. Besides being a small, compact and practical solution, *Vital Helmet* is able to adapt to different scenarios and, also important, it is low cost. Furthermore, our solution is versatile, since it enables to switch between sensors and improve the firemen performance, warning in advance of risky situations. Once each slave has its own microcontroller and all the data processing is done at the sensor, our general solution is adaptable to different types of sensors.

6.1 Contributions

After completing all the goals that were proposed and analyzing the results, we achieved some important contributions. First, we proposed a sensorized helmet module based on embedded circuits.

Moreover, we present some experimental results that can be used to improve our solution in the future. We also provide some programming code able to be used in several applications.

6.2 Future Work

After finishing this dissertation, we know that the system's application is not limited, there are still many phenomena to study, challenges to overcome. New features that can be developed to improved the helmet module, such as:

- First of all, it is crucial to calibrate the sensors. By the time this dissertation was submitted, this was not possible because the *Institudo de Ambiente* with whom our lab works does not have such high gases concentration. Nevertheless, we are already working in a calibration by comparison
- In order to have several slaves connected to the master at the same time, I^2C communication problems must be solved. The PIC24F datasheet exhibits several errata entries with respect to I2C communication. Such errata demand the firmware and even the architecture of our system to be optimized and redesigned. If we do not succeed in such task, the solution and future work must comprise the choice of a new protocol such as CAN, a bus protocol defined by the ISO 11898-1 standard. It could be necessary to change the formfactor. As we said previously in this dissertation, we are already dealing with this problem, trying a new approach once again
- In order to minimize power dissipation due to the possible wide variations in supply voltage a high precision voltage reference must be used
- Other important task to do is finish the camera and flashlight design and implementation
- If possible, a potentiometer could be placed at LMP output with the purpose to allow a calibration in the emergency scenario, i.e, changing the reference voltage leads to a full scale variation
- If necessary, more sensors may be added, since the way we implemented our slave module allows adding the desired number of sensors
- One of the major problem that firefighters have to face is the necessity of enter into a burning place looking for victims. Due to the dense smoke there is a lack of luminosity, thus, we propose, as a future work, the implementation of a thermal imaging camera

Appendix A

Appendix

A.1 Letter to ANPC

Ex.mo Senhor Francisco Grave Pereira

Presidente da Autoridade Nacional de Proteção Civil

Porto, 14 de junho de 2015

Assunto: Dados para conclusão de dissertação de mestrado

Exmo. Senhor Presidente da ANPC

Eu, Susana Margarida Ribeiro Pereira D'Eça, portadora do cartão de cidadão com o nº 14197104, bombeira de 3ª, na reserva na Associação Humanitária dos Bombeiros Voluntários de Valença, com o número mecanográfico 16070009 e aluna de engenharia eletrotécnica e de computadores na faculdade de Engenharia do Porto, encontro-me a concluir a dissertação no INESC -TEC, no Porto.

No âmbito da minha dissertação de mestrado cujo tema é "VitalHelmet – Towards a sensorized helmet for First Responders", venho solicitar o apoio de V.Exª. para o fornecimento de alguns dados, importantes para a minha dissertação.

Esta recolha de dados constitui uma fase de investigação que tem como propósito último, desenvolver e integrar um sistema autónomo para ser usado por bombeiros e capaz de medir a concentração de matérias perigosas e gases presentes num cenário de emergência.

Nesta fase pretendo recolher dados sobre:

- Em incêndios industriais (borracha, plásticos e metais, entre outras) quais os principais gases expelidos;
- Número de ocorrências por ano, de bombeiros feridos por intoxicação e/ou por queimaduras;
- Custo acarretado por bombeiro internado, nestas circunstâncias.

Antecipadamente grata pela sua atenção com elevada estima e consideração.

Sem outro assunto, apresento os melhores cumprimentos,

Susana Ribeiro D'Eça

(Susana Ribeiro D'Eça)

A.2 Hardware Design

Slave

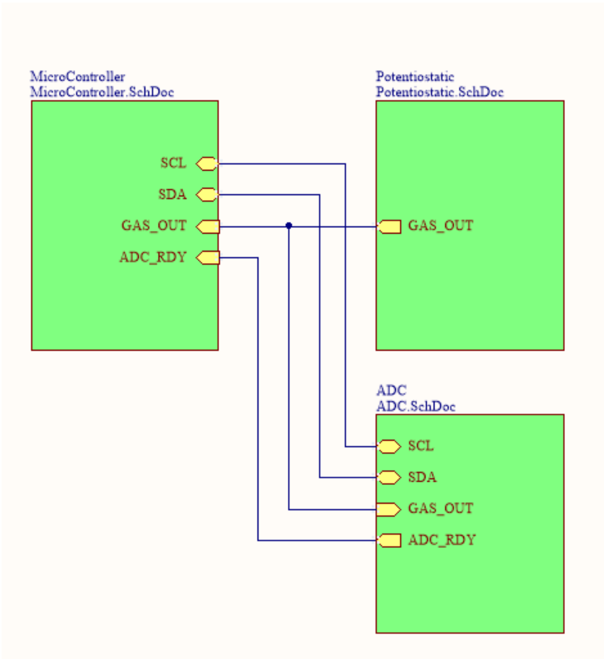


Figure A.1: Schematic of Slave PCB project

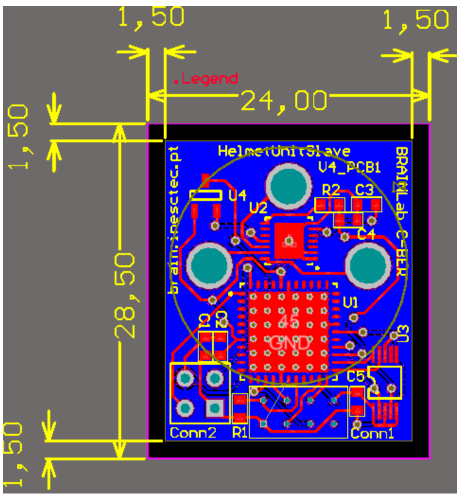


Figure A.2: 2-D Schematic of Slave PCB project

Master

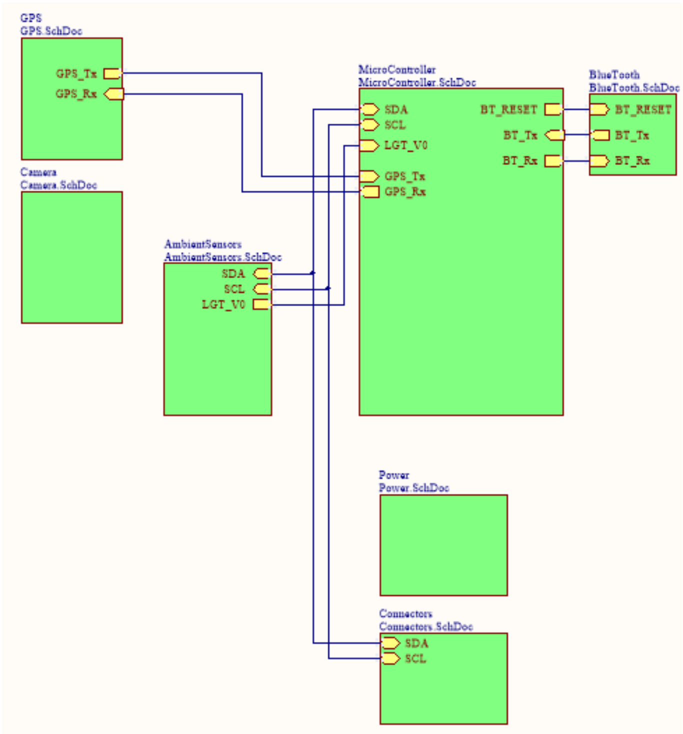


Figure A.3: Schematic of Master PCB project

Flashlight version

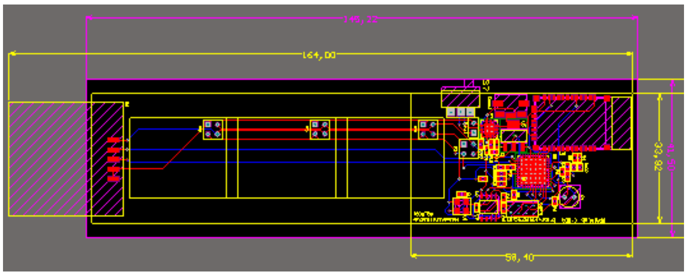


Figure A.4: 2-D Schematic of Master PCB project

Smallest version

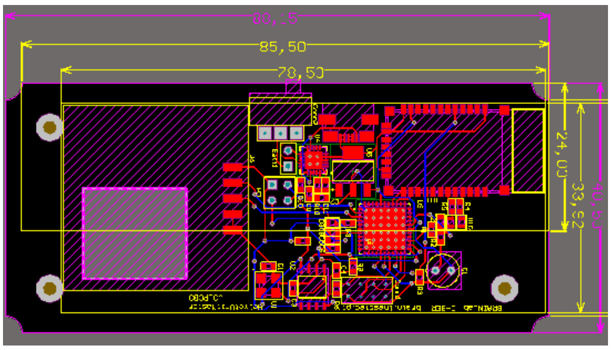


Figure A.5: 2-D Schematic of Master PCB project

A.3 Silicon Errata and Data Sheet Clarification of PIC24FJ64GA004 Family

PIC24FJ64GA004 Family Silicon Errata and Data Sheet Clarification

The PIC24FJ64GA004 family devices that you have received conform functionally to the current Device Data Sheet (DS39881**D**), except for the anomalies described in this document.

The silicon issues discussed in the following pages are for silicon revisions with the Device and Revision IDs listed in Table 1. The silicon issues are summarized in Table 2.

The errata described in this document will be addressed in future revisions of the PIC24FJ64GA004 family silicon.

Note:	This document summarizes all silicon errata issues from all revisions of silicon, previous as well as current. Only the issues indicated in the last column of Table 2 apply to the current silicon revision (**B8**).

Data Sheet clarifications and corrections start on page 17, following the discussion of silicon issues.

The silicon revision level can be identified using the current version of MPLAB® IDE and Microchip's programmers, debuggers, and emulation tools, which are available at the Microchip corporate web site (www.microchip.com).

For example, to identify the silicon revision level using MPLAB IDE in conjunction with MPLAB ICD 2 or PICkit™ 3:

1. Using the appropriate interface, connect the device to the MPLAB ICD 2 programmer/debugger or PICkit™ 3.
2. From the main menu in MPLAB IDE, select *Configure>Select Device*, and then select the target part number in the dialog box.
3. Select the MPLAB hardware tool (*Debugger>Select Tool*).
4. Perform a "Connect" operation to the device (*Debugger>Connect*). Depending on the development tool used, the part number *and* Device Revision ID value appear in the **Output** window.

Note:	If you are unable to extract the silicon revision level, please contact your local Microchip sales office for assistance.

The DEVREV values for the various PIC24FJ64GA004 family silicon revisions are shown in Table 1.

TABLE 1: SILICON DEVREV VALUES

Part Number	Device ID(1)	Revision ID for Silicon Revision(2)			
		A3/A4	B4	B5	B8
PIC24FJ64GA004	044Fh	3003h	3042h	3043h	3046h
PIC24FJ48GA004	044Eh				
PIC24FJ32GA004	044Dh				
PIC24FJ16GA004	044Ch				
PIC24FJ64GA002	0447h				
PIC24FJ48GA002	0446h				
PIC24FJ32GA002	0445h				
PIC24FJ16GA002	0444h				

Note 1: The Device IDs (DEVID and DEVREV) are located at the last two implemented addresses in configuration memory space. They are shown in hexadecimal in the format "DEVID DEVREV".

2: Refer to the *"PIC24FJXXXGA0XX Flash Programming Specification"* (DS39768) for detailed information on Device and Revision IDs for your specific device.

TABLE 2: SILICON ISSUE SUMMARY

Module	Feature	Item Number	Issue Summary	Affected Revisions[1]			
				A3/A4	B4	B5	B8
JTAG	—	1.	Persistent pull-up (RA3) when JTAG disabled.	X			
LVD	—	2.	No LVD interrupt with low-voltage condition at Reset.	X			
Core	Idle mode	3.	Clock failure trap fails in Idle mode.	X			
Core	Doze mode	4.	RAM read repeat on entering Doze mode.	X			
Core	BOR	5.	POR and BOR flags both set on BOR.	X			
Core	RAM	6.	RAM size implementation on some devices.	X			
A/D	—	7.	Unimplemented channels may be selected.	X			
A/D	—	8.	Missing midscale conversion code.	X			
A/D	—	9.	Device may not wake when convert on INT0 trigger is selected.	X			
I^{2}C	SDA Line State (I2C1)	10.	Line state may not be detected correctly.	X			
UART	—	11.	Reception failures in High-Speed mode.	X			
UART	—	12.	Erroneous baud rate calculations in High-Speed mode.	X			
UART	Auto-Baud	13.	Double receive interrupt with auto-baud reception.	X			
UART	Auto-Baud	14.	Insertion of spurious data with auto-baud reception.	X			
UART	Auto-Baud	15.	Auto-baud calculation errors causing transmit or receive failures.	X			
UART	Break Character Generation	16.	The UART module will not generate back-to-back Break characters.	X	X	X	X
Output Compare	—	17.	Single missed compare events under certain conditions.	X			
SPI	Enhanced Buffer mode	18.	Some flag bits are set at incorrect times in Enhanced Buffer mode.	X			
SPI	—	19.	Module in Slave mode may ignore $\overline{SS}$ pin and receive data anyway.	X			
SPI	Enhanced Buffer mode	20.	No SPI interrupt in Enhanced Buffer mode under certain conditions.	X			
I/O	—	21.	Spec change for V_{OL} and V_{OH}.	X			
I/O	—	22.	OSCO/RA3 driven immediately following POR.	X			
JTAG	—	23.	Sync loss in ICSP™ mode.	X			
RTCC	—	24.	Write errors to ALCFGRPT register.	X			
I^{2}C	Slave mode	25.	In Slave mode, ACKSTAT bit state change.	X			
I^{2}C	—	26.	Issues with write operations on I2CxSTAT.	X			
UART	IrDA®	27.	IR baud clock only available during transmit.	X			
I/O	PPS	28.	Issues with digital signal priorities with RP12 and RP18.	X			
UART	UERIF Interrupt	29.	No UERIF flag with multiple errors.	X	X	X	X

Note 1: Only those issues indicated in the last column apply to the current silicon revision.

TABLE 2: SILICON ISSUE SUMMARY (CONTINUED)

Module	Feature	Item Number	Issue Summary	Affected Revisions[1]			
				A3/A4	B4	B5	B8
UART	FIFO Error Flags	30.	PERR and FERR not correctly set for all bytes in receive FIFO.	X	X	X	X
Core	BOR	31.	Spontaneous BOR events with low-range VDD.	X	X	X	X
Core	Instruction Set	32.	Loop count errors with REPEAT instruction and R-A-W stalls.	X			
Memory	PSV	33.	False address error traps at lower boundary of PSV space.	X	X	X	
RTCC	—	34.	Decrement of alarm repeat counter under certain conditions.	X	X	X	
SPI	Master mode	35.	SPIIF and SPIBEN may become set early under certain conditions.	X			
I^{2}C™	Master mode	36.	Module may respond to its own master transmission as a slave under certain conditions.	X	X	X	X
I^{2}C	Slave mode	37.	Failure to respond correctly to some reserved addresses in 10-bit mode.	X	X	X	X
I^{2}C	—	38.	TBF flag not cleared under certain conditions.	X			
UART	—	39.	Erroneous sampling and framing errors when using two Stop bits.	X	X	X	X
Oscillator	SOSC	40.	Low-power SOSC unimplemented.	X			
Voltage Regulator	—	41.	Standby mode not available.	X			
Core	Code-Protect	42.	General code protection disables bootloader functionality.		X		
SPI	—	43.	Interrupts when SPI is operating in Enhanced Buffer mode.	X	X	X	X
UART	IrDA®	44.	RXINV bit operation is inverted in IrDA® mode	X			
Core	Doze Mode	45.	Instruction execution glitches following DOZE bit changes.	X	X	X	X
SPI	Master mode	46.	Spurious transmission and reception of null data on wake-up from Sleep (Master mode).	X	X	X	X
SPI	Master mode	47.	Inaccurate SPITBF flag with high clock divider.		X	X	X
SPI	Framed modes	48.	Framed SPI modes not supported.	X	X	X	X
Core	Data SRAM	49.	Higher current consumption during SRAM operations.		X	X	
I/O Ports	PORTA and PORTB	50.	Some I/O pin functions do not work correctly under certain conditions	X	X	X	X
A/D Converter	—	51.	Once the A/D module is enabled, it may continue to draw extra current	X	X	X	X

Note 1: Only those issues indicated in the last column apply to the current silicon revision.

A.4 Sensors Calibration

Gmail by Google

Susana D'Eça <sue.ribeiro.eca@gmail.com>

Calibração de Sensores

Susana D'Eça <susana.p.eca@inescporto.pt> 20 de maio de 2015 às 13:26
Para: joanavalente@ua.pt
Cc: Susana D'Eça <sue.ribeiro.eca@gmail.com>

Boa tarde,

O meu nome é Susana D'Eça e estou a fazer tese com o professor João Paulo Cunha na equipa Brain. Tal como o professor disse ontem na reunião, estou a trabalhar na monitorização de gases nas placas HelmetUnit.
Em anexo envio o método de calibração que a empresa aconselha para tentar perceber se é possível calibrar as minhas placas em Aveiro.
Agradeço desde já o tempo tomado.

Atenciosamente,

Susana Ribeiro D'Eça

INESC TEC TRINTA ANOS 1985—2015

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Gas Sensor Calibration.pdf
109K

Susana D'Eça <sue.ribeiro.eca@gmail.com>

FW: Fornecedores de gases

Joana Valente <joanavalente@ua.pt> 9 de junho de 2015 às 11:23
Para: "Susana D'Eça (sue.ribeiro.eca@gmail.com)" <sue.ribeiro.eca@gmail.com>, "Susana D'Eça (susana.p.eca@inesctec.pt)" <susana.p.eca@inesctec.pt>

Viva Susana

Os nossos equipamentos estão disponíveis quando quiserem. Não sei no entanto onde vão encontrar concentrações de NO_2 e CO suficientemente elevadas para medir alguma coisa… Tem oportunidade na sua actividade como bombeira para acompanhar um incêndio? As queimas que tivemos em Baião e Gestosa teriam sido o ideal. É uma pena que não tenham conseguido ir.

Abaixo envio contacto de fornecedores de gases.

A indicação que tenho do IDAD é que uma garrafa custa entre 200 e 400€ (não certificada, penso que não será necessário neste caso). É necessário ter cuidado porque além do preço em sis, alguns fornecedores cobram o aluguer da garrafa.

Cumprimentos

Joana

From: Alexandra Passos Silva
Sent: terça-feira, 9 de Junho de 2015 11:17
To: Joana Valente
Subject: Fornecedores de gases

Joana,

Contactos dos fornecedores:

LINDE	Eng. Manuel Carvalho Hugo Narciso	manuel.carvalho@pt.linde-gas.com Hugo.Narciso@pt.linde-gas.com
Praxair	Eng. Fernando Lima	Fernando_Lima@Praxair.com

Ar Líquido	Carla Abreu	carla.abreu@airliquide.com
Gasin	Eng. Fernando Lourenço	DASILVFM@gasin.com

Se precisares de mais alguma coisa, diz, pf.

Bjs

Alexandra Passos Silva

IDAD - Instituto do Ambiente e Desenvolvimento

Campus Universitário

3810-193 AVEIRO - Portugal

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Fax: +351 234 400 819

http://www.idad.ua.pt/

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