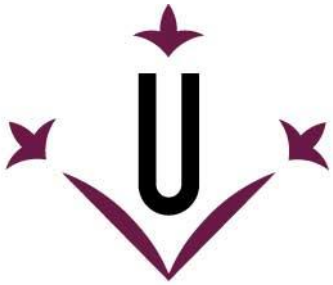
# Enhancement of the applications and functionalities of the Assistant Personal Robot platform

David Martínez Piqué



Universitat de Lleida

# TESI DOCTORAL

# Enhancement of the applications and functionalities of the Assistant Personal Robot platform

David Martínez Piqué

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Enginyeria i Tecnologies de la Informació

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# Enhancement of the applications and functionalities of the Assistant Personal Robot platform

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CERTIFICA:

Que la memòria "Enhancement of the applications and functionalities of the Assistant Personal Robot platform" presentada per David Martínez Piqué per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, 23 de març de 2021.

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# Resum

En aquesta memòria es presenta el treball d'investigació realitzat en el camp de les tecnologies de la informació y la tecnologia robòtica a través del desenvolupament y la millora de la plataforma robòtica APR (Assistent Personal Robòtic).

La plataforma robòtica APR va sorgir d'un projecte el qual es centrava en investigar nous mètodes y algoritmes per convertir a un robot mòbil en una eina amb serveis d'assistència per ajudar a persones discapacitades o de la tercera edat amb l'objectiu de millorar la seva qualitat de vida. Aquest projecte es va desenvolupar en el grup d'investigació de processat de senyal i robòtica de la Universitat de Lleida. El desenvolupament de la plataforma APR va progressar gracies a la implementació de nombroses aplicacions, el disseny de nous prototips APR i la publicació de diversos articles científics. En aquell moment, les noves característiques del robot mòbil no sol van aportar els serveis d'assistència pel qual va ser dissenyat inicialment, sinó que també va començar a convertir-se en una extraordinària eina d'investigació per desenvolupar nous coneixements basats en els conceptes d'Internet de les coses (IoT), la tecnologia de la informació (IT) o la intel·ligència ambiental (AmI).

En aquesta memòria es presenten quatre treballs d'investigació relacionats amb el desenvolupament y la millora de les aplicacions y funcionalitats de la plataforma APR. El primer treball presenta el desenvolupament d'un dispositiu sensor compacte destinat a ser utilitzat com una eina portàtil de recol·lecció y registre de dades ambientals. El segon treball presenta el desenvolupament d'una matriu de sensors de gasos de baix cost per la detecció de fuites de gasos en entorns complexes. El tercer treball proposa un mètode que permet aplicar tècniques SLAM en un LIDAR 2D inclinat cap al terra amb el fi de detectar forats o petits objectes que normalment no es poden detectar quan s'utilitza un LIDAR 2D en posició horitzontal. Finalment, el quart treball presenta la implementació d'una roda omnidireccional no òptima y l'anàlisi de la reducció de vibracions

mitjançant la utilització d'un sistema de suspensió passiva. El disseny de la nova roda omnidireccional no òptima té com a objectiu expandir les capacitats del robot mòbil, reduint el cost d'implementació de les rodes i aportar noves possibilitats de mobilitat en ambients interiors o exteriors.

# Resumen

Esta memoria presenta el trabajo de investigación realizado en el campo de las tecnologías de la información y la tecnología robótica a través del desarrollo y la mejora de la plataforma robótica APR (Asistente Personal Robótico).

La plataforma robótica APR surgió de un proyecto en cual se centraba en investigar nuevos métodos y algoritmos para convertir a un robot móvil en una herramienta con servicios asistenciales para ayudar a personas discapacitadas o mayores con el objetivo de mejorar su calidad de vida. Este proyecto se desarrolló en el grupo de investigación de procesador de señal y robótica de la Universidad de Lleida. El desarrollo de la plataforma APR progresó gracias a la implementación de diversas aplicaciones, el diseño de nuevos prototipos APR y la publicación de diversos artículos científicos. En ese momento, las nuevas características del robot móvil no solo aportaron las servicios de asistencia por las cuales fue diseñado, sino que también empezó a convertirse en una extraordinaria herramienta de investigación para desarrollar nuevo conocimiento basado en conceptos como el Internet de las cosas (IoT), la tecnología de la información (IT) o la inteligencia ambiental (AmI).

En esta memoria se presentan cuatro trabajos de investigación relacionados con el desarrollo y la mejora de las aplicaciones y funcionalidades de la plataforma APR. El primer trabajo presenta el desarrollo de un dispositivo sensor compacto destinado a ser utilizado como una herramienta portátil de recolección y registro de datos ambientales. El segundo trabajo presenta el desarrollo de una matriz de sensores de gas de bajo coste para la detección de fugas de gases en entornos complejos. El tercer trabajo propone un método que permite aplicar técnicas SLAM en un LIDAR 2D inclinado hacia el suelo con el fin de detectar agujeros u objetos pequeños que normalmente no se detectan cuando se utiliza un LIDAR 2D en posición horizontal. Finalmente, el cuarto trabajo presenta la implementación de una rueda omnidireccional no óptima y la reducción de vibraciones mediante la utilización de un sistema de suspensión

pasiva. El diseño de la nueva rueda omnidireccional no óptima tiene como objetivo expandir las capacidades del robot móvil, reduciendo el coste de implementación de las ruedas y aportar nuevas posibilidades de movilidad en ambientes interiores o exteriores.

# Summary

This memory presents the research work performed in the field of information technologies and robotics technology through the development and improvement of the Assistant Personal Robot (APR) platform.

The APR platform was created in a project focused on investigate new methods and algorithms to convert a mobile robot into an assistive service tool in order to help disabled or elderly people with the objective to improve their quality of life. This project was developed on the Signal Processing and Robotics Research Group from the University of Lleida. The development of the APR platform has enabled the implementation of multiple applications and the design of new APR prototypes. At that moment, the new features of the mobile robot platform not only provided the assistive services that was initially conceived on, but it also started to become a versatile research tool to develop new knowledge based on concepts such as Internet of Things (IoT), Information Technologies (IT) or Ambient Intelligence (AmI).

This memory presents four research works related with the development and improvement of the applications and functionalities of the APR platform. The first work presents the implementation of a compact sensor device intended to be used as a portable gathering ambient data tool based on standard protocols. The second work presents the development of a low-cost gas sensor array for early gas leak detection. The sensor device aims to detect multiple gas sources in complex environments. The third work proposes a method to perform the SLAM technique on a fixed tilted-down 2D LIDAR in order to detect holes or small objects that usually remains undetected when using a fixed horizontal 2D LIDAR. Finally, the fourth work presents the implementation of a non-optimal omnidirectional wheel and the analysis of the reduction of vibrations through the use of a passive suspension system. The design of the new non-optimal omnidirectional wheel aims to expand the capabilities of the mobile robot, reducing the manufacturing

cost and providing new mobility possibilities in indoors and outdoors environments.

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# Chapter 1

# Introduction

The globalization of the information and communications technologies (ICT) have provided the development of new technologies intended to establish a network of physical devices that includes embedded sensors, software and other technologies for the purpose of connecting and exchange data with other devices through the Internet, also known as, Internet of Things (IoT). The development of this new technologies have fostered the emergence of new concepts such as Ambient Intelligence (AmI), which refers to electronic devices that are sensitive and responsive to the presence of people in order to automatize daily routines, taking decisions and keeping a healthy environment.

Robotics technology is considered one of the most important fields that has the potential to develop new applications that positively transform work practices, raise efficiency, enhance the services and safety levels, and consequently facilitate and improve the quality of people life. The major increase of robotics technology is caused by the competitiveness of the manufacturing industries and the automation of industrial processes. The increasing advances on such fields also fostered the inclusion of robotics in other life aspects that recently were only performed by humans, such as the inclusion of assistive robots at home. The development of these assistive robots is generally focused on assisting and monitoring the well-being and safety of disabled or elderly people. Although the human expertise is impossible to substitute, the inclusion of these kind of robots can provide help in form of environmental monitoring systems, alarm reminders or guiding systems.

The development of this Thesis is based on the participation of different projects that addresses the use of both, robotics and information technologies.

## 1.1. Previous related projects

The development of this Thesis is based on previous research work supported by two different projects performed by previous PhD students of the Signal Processing and Robotics Research Group from the University of Lleida. The next sections describe the main objectives of these two projects.

### 1.1.1. SIGVOL project

The first project was titled “Signal enhancement for chemical instrumentation: applications in volatile metabolomics and mobile robotics olfaction” and has the acronym of SIGVOL. This project was granted by the Spanish Ministry of Science and Innovation (reference: TEC2014-59229-R). The objective of this project was the development of new signal processing techniques in order to improve the performance of chemical instruments. Then, the project focuses on the processing and improvement of the information obtained with chemical sensors carried out by a mobile robot in order to detect Volatile Organic Compounds (VOCs) in different environments.

### 1.1.2 APR project

The second project was titled “Asistente Personal Robótico” and has the acronym of APR. This project was granted by Indra, Universitat de Lleida and Fundación Adecco (reference: X12014). The main objective of this project was the development of new algorithms and methods to convert a high mobility robot in an Assistant Personal Robot (APR) with telepresence capabilities. Then, the project was expanded though another project titled “Analysis of the application of a personal robotic assistant at home in the case of people with disabilities”. This project was granted by RecerCaixa, Associació Catalana d’Universitats Públiques

(ACUP) and Obra Social “la Caixa”. The main objective was the development of assistive services in the Assistant Personal Robot to operate at home of an impaired or elderly people in order to improve their quality of life. The specific objectives focused on developing assistive roles for disabled or elderly people such as walking assistant systems, social interaction systems, monitoring environmental conditions, surveillance, fall detections and the evaluation of the improvement of the quality of life when using the APR at home.

## 1.2. Previous related PhD Theses

The research work carried out in these projects fostered the development of three previous doctoral theses. The following sections presents a summary of the three doctoral theses and papers published previously. The main idea is to provide an overview of the progress made around the SIGVOL and the APR project.

### 1.2.1. Thesis title: Application of autonomous mobile platforms for environmental supervision and gas leakage localization

The development of this doctoral thesis was funded by the SIGVOL project and was carried out by Daniel Martínez Lacasa. This doctoral thesis proposed the development of new Ambient Intelligent systems focused on the supervision of the environmental conditions by using a mobile robot. The results and conclusions were published in four papers. The first paper titled “A proposal of a Multi-agent System Implementation for the Control of an Assistant Personal Robot” [1], proposed a multi-agent architecture able to execute different robot processes simultaneously without decreasing global performances. The second paper titled “Ambient Intelligence Application Based on Environmental Measurements Performed with an Assistant Mobile Robot” [2], described the development of a mobile robot able to patrolling and analyzing the ambient information of an area in order to detect anomalies. The third paper titled “Measuring Gas Concentration and Wind Intensity in a Turbulent Wind Tunnel with a Mobile Robot” [3], proposed the measurement of gas concentration and wind intensity inside a

custom wind tunnel by using mobile robot. In this case, the objective was to create information maps with the distribution of gas and wind concentrations inside the wind tunnel at different operations conditions. Finally, the fourth paper titled “A Mobile Robot Agent for Gas Leak Source Detection” [4], proposed the development of an automated mobile robot able to detect the localization of a gas leak source. The mobile robot used gas and wind sensors to estimate the source of the gas leak.

### 1.2.2. Thesis title: Improvement of the implementation of an Assistant Personal Robot

The development of this doctoral thesis was carried out by Javier Moreno Blanc. This doctoral thesis proposed the improvement of the implementation of an Assistant Personal Robot from the mechanical point of view in order to foster the development new applications in domestic environments. The results and conclusions were published in four papers. The first paper titled “Design, Implementation and Validation of the Three-Wheel Holonomic System of the Assistant Personal Robot (APR)” [5], described the three-wheel omnidirectional motion system in terms of mechanical design and electronic control. This paper validated the estimation of trajectory comparing the displacement estimated between the SLAM technique and the internal odometry. The second paper titled “Experimental Characterization of the Twin-Eye Laser Mouse Sensor” [6], performed an experimental characterization of a laser mouse sensor intended to be used as a redundant low cost localization system in an Assistant Personal Robot. The third paper titled “Evaluation of the Color-Based Image Segmentation Capabilities of a Compact Mobile Agent Based on Google Android Smartphone” [7], presented a mobile robot based on a Google Android Smartphone as a control unit. The application and performances implementing image segmentation were tested in a small soccer mobile robot before its application in an APR. Finally, the fourth paper titled “A combined approach to the problem of opening a door with an assistant mobile robot” [8], proposed the detection of different types of door handles and the development of a mechanical device to open doors integrated in the design of an Assistant Personal Robot.

### 1.2.3. Thesis title: Improving the quality of life of older adults and people with reduced mobility through an Assistant Personal Robot

The development of this doctoral thesis was funded by the APR project and was carried out by Eduard Clotet Bellmunt. This doctoral thesis proposed the development and improvement of the Assistant Personal Robot platform. The objective was the use of a mobile robot for telepresence services, the improvement of the interaction with people with mobility impairments and the implementation of an ambient monitoring tool. The results and conclusions were published in four papers. The first paper titled “Assistant Personal Robot (APR): Conception and Application of a Tele-Operated Assisted Living Robot” [9], presented the mechanical, electronic and software implementation of a tele-operated mobile robot designed to provide social and assistive services to impaired and elderly people. The second paper titled “Extending the application of an Assistant Personal Robot as a walk-helper tool for people with reduced mobility” [10], proposed the APR mobile robot as a walk-helper tool, providing physical support and guidance by using the onboard sensors in order to avoid obstacles. The third and four paper are titled “Preliminary application of an Assistant Personal Robot as an ambient monitoring tool” [11] and “Automatic supervision of temperature, humidity, and luminance with an Assistant Personal Robot” [12], proposing the implementation of an autonomous mobile robot able to monitor the ambient conditions by the implementation of the SLAM technique and the automatic generation of reports in case of identify possible hazardous environmental conditions.

## 1.3. The Assistant Personal Robot platform

This section describes the evolution of the APR platform thanks to the research work reflected on the previous doctoral theses. The section presents the different mobile robot prototypes, the main features and the new improvements and functionalities developed.

The Assistant Personal Robot (APR) platform arose from the APR project which was focused on investigate new methods and algorithms to convert a

mobile robot in a personal robotic assistant that operates at home, interacting with people with mobility impairments in domestic environments. In this direction, the first version of the APR, named APR-01, was designed as a remotely controlled telepresence mobile robot in order to provide social and assistive services to impair or elderly people. The second version of the APR, named APR-02 was designed to include an autonomous navigation system, including a passive suspension system and improving the control of the arms. The robust motion control of the APR-02 provided the assistive services and become versatile research tool for any type of experiments based on a mobile robot. Finally, this doctoral thesis is focused on the development of the third APR version, named APR-03 which is a clone of the APR-02 but with the objective to improve the functionalities of the APR platform by the inclusion of new embedded sensors, improving the obstacle avoidance detection, developing new mobile robot-based tools and improving the motion system in order to extend its application in indoors and outdoors environments.

### 1.3.1. APR-01

Clotet et al. [9] presented the first Assistant Personal Robot (APR-01) (Fig. 1.1) as a remotely controlled robotic platform in order to provide social and assistive services for the impaired and elderly people. The APR-01 has a humanoid shape which includes a tactile screen, a front camera, two arms, a LIDAR sensor and three optimal omnidirectional wheels. The system is powered by three 12Ah 12V lead acid batteries.

The main processing unit is based on an Android tablet that also drives the interaction between the user and the robot. The front camera provides a wide field of view of the person that is under the control of the robot. The head is controlled by two DC motors able to perform pan and tilt movements in order to maximize the robot vision. The two arms are based on two DC motors in order to provide a slight interaction with the environment. The mobile robot also included an additional arm designed by Moreno et al. [8] as a first approach to the problem of opening a door with a mobile robot. This mobile robot included a LIDAR sensor

that provides two dimensional point cloud measurements, allowing the detection of obstacles in order to prevent collisions when the robot is in movement. The omnidirectional motion system was designed and validated by Moreno et al. [5], providing free rotational and translational motion in any direction by individually controlling the power applied to the motors that drives the omnidirectional wheels.

### 1.3.2. APR-02

The APR-02 (Fig. 1.1) was the second improved Assistant Personal Robot prototype. The main features included on this prototype were the following: (1) substitution of the lead acid batteries (Pb – 12Ah 12V) for lithium iron phosphate batteries (LiFePO4 – 15Ah 12V), reducing the overall weight of the APR mobile robot while increasing the autonomy; (2) inclusion of a high-end desktop computer attached at the base of the robot, required for the development of the autonomous navigation system and the inclusion of embedded sensors; (3) implementation of a passive suspension system in order to reduce the vibrations generated by the optimal omnidirectional wheels [13]; (4) substitution of the two DC motors of the arms with servomotors, four in each arm, providing interaction with environment and the development of different types of movements such as saluting, dancing, pointing, etc. The implementation of all these features fostered the development of new applications: as an autonomous agent [12] for temperature, humidity and luminance supervision and as a walk-helper tool [10].

**Fig. 1.1.** Researcher in front of the three APR prototypes: APR-01 (left), APR-03 (center) and APR-02 (right).

### 1.3.3. APR-03

The APR-03 (Figure 1.1) was the third version of the Assistant Personal Robot. The APR-01 platform was developed as an assistive service tool with telepresence functionalities in order to help impaired or elderly people. Then, the APR-02 platform was improved with the development of an improved navigation system. This new feature not only provided the development of new automatic monitoring systems and walk-helper tools related with the main objective of the project, but also opened the possibility of using the APR platform as a versatile research tool in different research fields. Initially, the APR-03 was developed as a clone of the APR-02, then the APR-03 became the experimental tool and start point of this doctoral thesis focused on the improvement of the electronic, mechanical and computer systems and in proposing new algorithms, methods, and sensor systems in order to improve the overall functionalities of the APR platform.

## 1.4. PhD Thesis projects

The development of this doctoral thesis have been funded by two specific projects: the ARALLAR project and the AGEN2 project. This two projects expanded the original functionalities of the Assistant Personal Robot. The next sections describe the main objectives of both projects. The results and conclusions of this projects are part of the development of this doctoral thesis.

### 1.4.1. ARALLAR project

The first project is titled “Aplicació d’un robot assistencial a la llar”, acronym ARALLAR, was funded by the UdL Impuls – Banco Santander (reference: X15016). The ARALLAR project was based on the APR mobile robots. The main objective was the development of new functionalities in an APR mobile robot by the design of an improved control systems and the inclusion of new sensors. The project proposed new assistive services related with the Ambient Intelligence discipline. The development of this project allowed the development of compact multi-sensing devices detailed in the fourth chapter of this Thesis and the development of a new application to detect gas leak sources detailed in the fifth chapter of this Thesis.

### 1.4.2. APR PLUS project

The second project is titled “APR PLUS” and was funded by SCT Taller Electrònic (reference: 030490). The aim of the APR PLUS project was the improvement of the APR prototypes with new control devices in order to improve the functionalities of an assistant personal robot. The development of this project proposed a new methodology to self-locate the position of a mobile robot by using a fixed tilted-down 2D LIDAR detailed in the sixth chapter of this Thesis and the implementation of a non-optimal omnidirectional wheel detailed in the seventh chapter of this Thesis.

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# Chapter 2

# Objectives

The main objective of this thesis is the development and improvement of the overall functionalities of the Assistant Personal Robot prototypes. This thesis summarizes four works proposed to provide solutions to different problems: (1) the supervision of ambient conditions in order to improve the quality of people life, (2) the detection of potentially harmful ambient conditions in order to prevent human exposition, (3) the improvement of the detection capabilities of a 2D LIDAR in order to provide a better understanding of the environment, and (4) the extension the functionalities of the mobile robotic platform by implementing new omnidirectional wheels with low manufacturing cost and outdoor capabilities.

The specific objectives of this Thesis are:

1. Design, development and implementation of a compact sensor device intended to be used as a portable gathering ambient data tool. The exchange of information between the sensor device and the Host device using standard protocols.

2. Apply a low-cost gas sensor array for early gas leak detection. The gas sensing device has to be attached in the mobile robot while performing routine explorations in an indoor environment.

3. Explore the possibilities of using a 2D tilted-down LIDAR for detection and self-location. The usage of a fixed 2D tilted-down LIDAR on the mobile robot has the motivation to detect holes or small

objects placed on the ground that remain undetected when using a fixed horizontal 2D LIDAR.

4. Design and implementation of a non-optimal omnidirectional wheel in order to expand the functionalities of the mobile robot platform. The advantage of the non-optimal omnidirectional wheel is to take advantage of the large gap between the free rollers to provide more traction in outdoor surfaces.

# Chapter 3

# PhD Thesis structure

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The development of this PhD Thesis has been performed in the Signal Processing and Robotics Research Group which is a member of the INSPIRES center (Institut Politècnic d'Innovació i Recerca en Sostenibilitat, centre de recerca de la Universitat de Lleida). This Thesis has been partially funded by the University of Lleida and the UdL-Impuls 2017 grant. This Thesis is structured in four chapters corresponding to four published papers. The impact factor of the published papers are indicated according the Scimago Journal Rank (SJR) and the Journal Citation Reports (JCR).

The papers published are:

- Palacín, J.; Martínez, D.; Clotet, E.; Tresanchez, M. Implementation of a Compact Wearable Temperature, Pressure, Humidity and Gas Sensing Device. Advances in Intelligent Systems and Computing 2019, 1018, 825-830. DOI: https://doi.org/10.1007/978-3-030-25629-6_129 Journal indexed as Q3 in Computer Science by Scimago Journal Rank (SJR).

- Palacín, J.; Martínez, D.; Clotet, E.; Pallejà, T.; Burgués, J.; Fonollosa, J.; Pardo, A.; Marco, S. Application of an Array of Metal-Oxide Semiconductor Gas Sensors in an Assistant Personal Robot for Early Gas Leak Detection. Sensors 2019, 19(9), 1957. DOI: https://doi.org/10.3390/s19091957

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  Journal indexed as Q1 in Instruments and Instrumentation by Journal Citation Reports (JCR) in 2019.

The Assistant Personal Robot was conceived as an assistive robot for telepresence purposes and assistive services in order to improve the quality of life of older adults or people with mobility impairments. This initial conception is in constant evolution due to the new features added to the Assistant Personal Robot during the last years. Currently, the mobile robot APR is used as scientific platform to develop new knowledge in concepts such as Internet of Things (IoT), Information Technology (IT) and Ambient Intelligence (AmI).

The following four chapters of this Thesis are focused on the development and improvement of the overall functionalities of the APR platform. Figure 3.1 shows the structure and relationships between the works developed. The first work presented in chapter 4 proposes the implementation of a compact multi-sensing device as a portable monitoring ambient data tool. The work presented in chapter 5 proposes the application of a low-cost gas sensor array in a mobile robot as an early gas leak detector. The work presented in chapter 6 proposes mobile robot self-localization with a 2D tilted-down LIDAR. Finally, in chapter 7 is proposed a design and implementation of a non-optimal omnidirectional wheel.

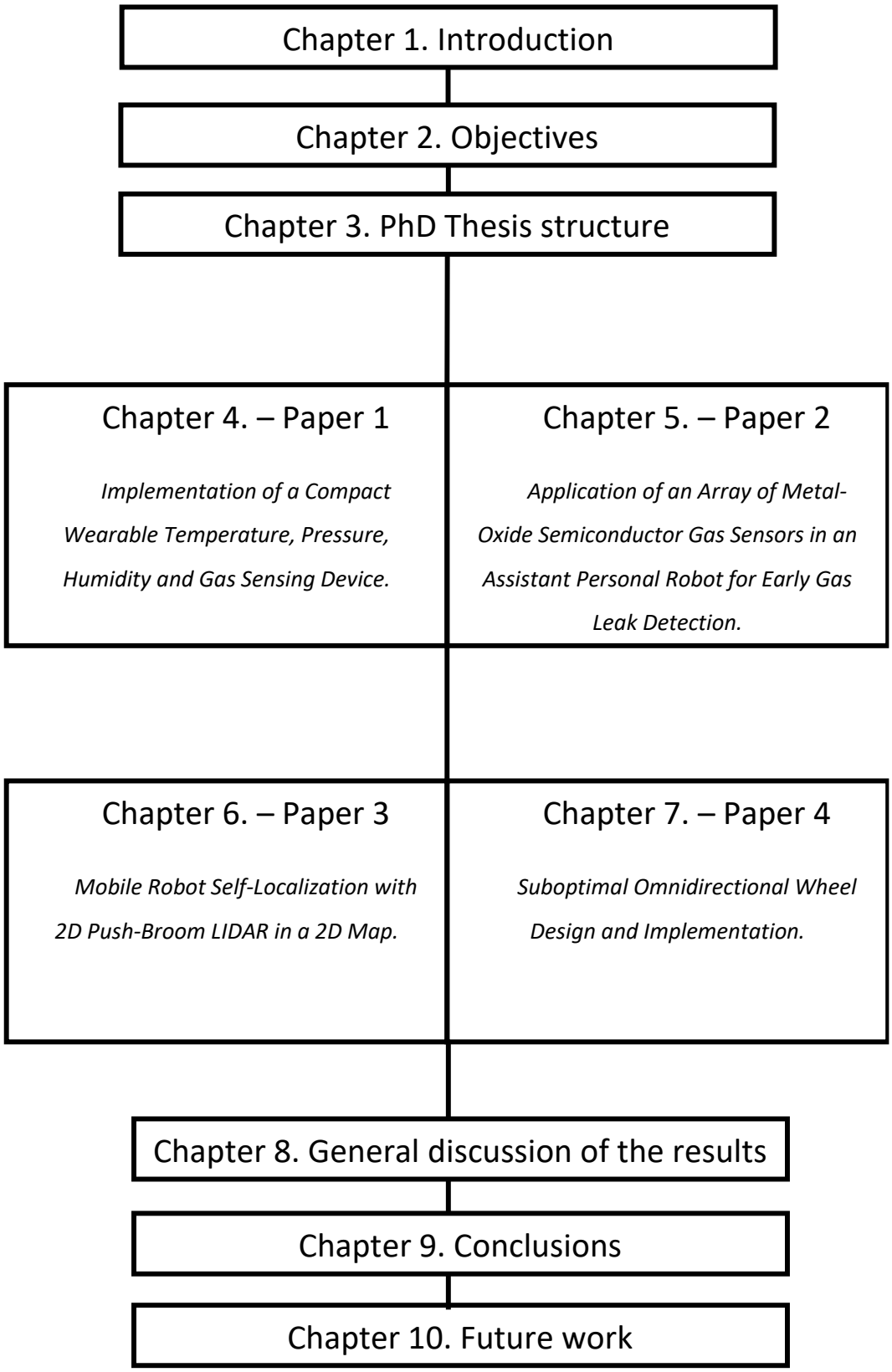


**Fig. 3.1.** PhD Thesis structure.

# Chapter 4

# Implementation of a custom, wearable and compact multi-sensing device

## 4.1. Introduction

During the last decades the use of portable devices has increased in all aspects of our lives. A portable device simply involves a small, thin, and lightweight device that is easy to carry and hold. The main examples are smartphones, laptops or smart watches. However, the small Plug-and-Play (PnP) devices also are portable devices such as the USB drives, external hard disks or webcams. These Plug-and-Play (PnP) devices usually are connected with a Host device through a USB connector. Therefore, the design and implementation of new portable Plug-and-Play (PnP) sensors devices has become an interesting subject in the field of Ambient Intelligence.

Ambient Intelligence pursues the automated monitoring of the environmental parameters in an indoor areas. The objective is to maintain the adequate levels of the ambient conditions for the human living. The use of portable sensors as a tool to measure environmental parameters provides more information of the surroundings than a static sensor network. For example, a portable sensor attached in a mobile robot or a portable sensor connected to our smartphone.

This chapter presents a paper describing the design, development and implementation of a compact and portable multi-sensing device able to measure

temperature, pressure, humidity and gas sensor resistance. The multi-sensing device is intended to be used as a portable gathering ambient data tool with simple connectivity to any Host device for research, industrial or educational purposes.

## 4.2. Contributions to the state of the art

In the scientific literature, there are several contributions on the development of portable sensor devices that have inspired this work. For example, Oprea et al. [1] presented the development of a low-power temperature, gas and humidity sensor on plastic substrates. The device can be used as a portable device due its small size but the sensor data is send through an I2C to USB adapter that needs the usage of a closed-source software program. Fang et al. [2] proposed the development of a micro weather station, which can sense temperature, relative humidity, pressure, and wind speed and direction. On the medical field, Hermans et al. [3] presented a portable multi-sensor data-logger for electrocardiography (ECG) measurement in harsh environments. On the chemical field, Massie et al. [4] carried out a detailed investigation in order to design a portable optical sensor for methane gas detection. An outdoor portable sensor application is presented by Yi et al. [5], where is described a modular sensor system for urban air pollution monitoring. Finally, Adiono et al. [6] presented a portable device for humidity and temperature sensing as an indoor environmental monitoring tool.

The paper presented in this chapter proposes the implementation of a portable multi-sensing device using the BME680 sensor. The paper focuses on the software implementation of an automatic task able to perform periodically readings of the sensor device and sending the data through a serial port by the development of the USB Communication Device Class (CDC). The objective is to develop a portable gathering ambient data tool capable to measure temperature, pressure, humidity, and gas resistance. The new contributions of the paper resides on the number of environmental parameters measured, the small size of the multi-sensing device developed and the conventional protocol used for the communication. This last contribution allows an easy connection with the APR mobile robot prototypes.

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# Chapter 5

# Early gas leak detection using a mobile robot with a low-cost gas sensor array

## 5.1. Introduction

The continuous trend of the globalization in the information technologies has allowed the emergence of new concepts such as Ambient Intelligence (AmI). The Ambient Intelligence proposes the development of intelligent environments with electronic devices that are sensitive and responsive to the presence of the human-living. The objective of this technology is to provide an intelligence system able to automate human daily routines while maintaining appropriate environmental conditions in indoor areas. The ambient conditions such as temperature, humidity, luminance or harmful gases must be supervised, since they can have a direct impact on health and safety.

The introduction of mobile robots as a monitoring tool enabled automatic supervision of the ambient conditions. The main advantage is the free occupancy of the sensor at any point of the environment and avoid the deployment of sensor networks. This chapter focuses on the inclusion of gas sensors in a mobile robot to avoid exposing humans in dangerous environments. Previous works characterized the behavior of a gas agent [1] and estimated the localization of the gas leak source in an indoor environment [2]. The conclusions drawn from these works laid the basis of the application developed in this chapter.

This chapter presents the application of a low-cost Metal-Oxide (MOX) gas sensor array in a mobile robot for early gas leak detection. The chapter presents a

paper proposing the characterization of a low-cost gas sensor array by training a partial least square discriminant analysis (PLS-DA) classifier with air, ethanol and acetone as output classes. Several experiments confirmed the early detection capabilities of the mobile robot which represent a step forward for gas source localization on real and challenging indoor environments.

## 5.2. Contributions to the state of the art

During the last decade, the integration of mobile robots equipped with gas sensors have derived on a discussion to solve the Gas Source Localization (GSL) problem. The GSL consists on developing an algorithm able to find the source of a released chemical. Different algorithms have been proposed in the scientific literature which can be classified into reactive plume tracking, plume modeling, and long-range sensing (Vision) and local sensing (Olfaction, Anemometry) [3]. An example of mobile platform for outdoor applications is described in [4] which presents an autonomous gas detection system to assess the measurement of specific gas concentrations using an unmanned aerial vehicle. An example of mobile platform for indoor applications is presented in [5] which deals with the problem of gas source localization by a mobile robot with gas and wind sensing capabilities. Generally, the methods presented focuses in the assumption of a single gas source. However, Hernandez et al. [6] proposes an algorithm that creates gas concentration maps on present of multiple gas sources using an array of Metal-Oxide (MOX) gas sensors. The great advantages of Metal-Oxide (MOX) gas sensors is the saving cost, weight, and space but also have disadvantages such as their lack of selectivity and cross-sensitivity with temperature and humidity. The selectivity of the system can be increased by using an array of Metal-Oxide (MOX) gas sensors operating at different temperatures which is one of the solutions adopted in the paper presented.

The paper presented in this chapter proposes the application of a low-cost array of Metal-Oxide (MOX) gas sensors on board of an Assistant Personal Robot (APR). The mobile robot is able to explore indoors environments by tele-controlled or autonomous navigation. The objective is the inclusion of gas sensing

capabilities in order to develop an early gas leak detection system. The sensing device is composed by 16 low-cost Metal-Oxide (MOX) gas sensors which were characterized through performing several experiments in order to train a multivariate classification model for air, ethanol and acetone detection. The new contributions of the paper presented reside in the number of parallel Metal-Oxide (MOX) gas sensors used, the low concentrations of gas detected, the multiple gas sources experimented and the real and complex scenario proposed. The combination of all these contributions allow the successful validation of the application of an array of Metal-Oxide (MOX) gas sensors in a mobile robot for early gas leak detection in a real case scenario.

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Journal indexed as Q1 in Instruments and Instrumentation by Journal Citation Reports (JCR).

# Chapter 6

# Mobile robot self-localization and collision avoidance using a 2D tilted-down LIDAR

## 6.1. Introduction

This chapter presents a 2D LIght Detection And Ranging (LIDAR) sensor application on a mobile robot platform. The chapter presents a work describing the potential of using a 2D tilted-down LIDAR for improving the detection of low-height objects and stairs which cannot be detected by a fixed horizontal 2D LIDAR. The work presented is mainly focused on proposing a methodology for mobile robot self-localization with a fixed 2D tilted-down LIDAR.

The development of LIDAR sensors fostered the development of autonomous mobile robots. There are a large number of scientific papers focused on taking profit of the LIDAR sensors to develop obstacle avoidance systems, autonomous navigation systems and 3D reconstruction of the environment. Generally, mobile robots include a fixed horizontal 2D LIDAR that produces enough point cloud data to represent a 2D plane of the environment. However, this data does not include objects that are below or above the scanned plane. This problem has been solved during the last years by tilting down/up or spinning/rolling a 2D LIDAR with a motorized unit or directly using a 3D LIDAR device. Nevertheless, adopting these solutions in a mobile robot requires the inclusion of a motorized

unit and complex calibration methods, increasing its control complexity and cost. In this direction, the work presented proposes a methodology for mobile robot self-localization with a fixed tilted-down 2D LIDAR that has the advantage of avoiding the use of a motorized unit.

## 6.2. Contributions to the state of the art

During the last years, most of the research works have focused on solving the limited field of view of the 2D LIDAR sensors by using a motorized unit attached to the 2D LIDAR sensor in order to obtain more information of the surroundings. For example, Lit et al. [1] proposed a 2D LIDAR with a Pan-Tilt mechanism to obtain multi-layer information. Ohno et al. [2] developed a 3D laser scanner by using a 2D Laser Range Finder and a Pan-Tilt base with the objective to detect moving objects between scans. Alismail et al. [3] presented an automatic algorithm to calibrate a spinning 2D LIDAR using generic scenes without the need for specialized calibration targets. Finally, Zhu et al. [4] proposes a calibration method when using multiple 2D LIDAR sensors. The main conclusion is that a calibration method is required when a motorized unit is used because the optical center of the 2D scan planes depends on the inclination. An example of rotating a 2D LIDAR without the need of a calibration procedure is presented in [5], where the optical center is the same for the different scanned planes. The paper presented in this chapter was inspired on the work of Takahashi et al. [6] which developed an obstacle avoidance system for a mobile robot by using a fixed tilted-down 2D LIDAR for detect low-height obstacles and slopes. The new contribution of the paper presented is the proposal of a methodology to self-locate the position of a mobile robot by using a fixed tilted-down 2D LIDAR. The experimental evaluation performed has proved that the self-localization is possible by detecting and deleting the ground and ceiling points, projecting the remaining points in the horizontal plane of a reference 2D map previously obtained with a 2D horizontal LIDAR, and finally applying the simultaneous localization and mapping (SLAM) technique. The main advantage of the proposed methodology on this chapter is the avoidance of using a motorized device to change the tilt of

the LIDAR in order to combine the collision avoidance and mobile robot self-localization characteristics, discarding complex calibration algorithms, mechanical movement parts and reducing the overall cost.

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# Chapter 7

# Design, implementation and vibration analysis of a non-optimal omnidirectional wheel

## 7.1. Introduction

This chapter presents the development of a non-optimal omnidirectional wheel for the APR mobile robot prototypes. The chapter presents a work that evaluates if the APR can take advantage of its passive suspension system in order to use non-optimal omnidirectional wheels. The paper presented is focused on a set of experiments in order to compare the vibrations generated when using optimal and non-optimal omnidirectional wheels and verify the possibility of taking advantage of the non-optimal gap to operate on rough surfaces.

Omnidirectional wheels are widely used on mobile robot platforms in order to perform arbitrary motion in any direction without changing the direction of the wheels. Generally, the optimal design of an omnidirectional wheel consist on the minimization of the gap between the free rollers in order to maximize the contact with the floor and minimize the generation of vibrations. Nevertheless, a tall and fast mobile robot usually also need a suspension system in order to reduce the vibrations generated on the highest part of the robot.

In one hand, the work presented describes the design of a non-optimal omnidirectional wheel based on 3D printing techniques in order to reduce the manufacturing cost. And in the other hand, the implementation of the non-optimal omnidirectional wheel is evaluated in terms of generation of vibrations.

## 7.2. Contributions to the state of the art

During the last years, omnidirectional wheels have been widely used in logistics, robotics and industry. The design of the different omnidirectional wheel configurations have provided the development of multiple mobile robots platforms able to perform 3 degree-of-freedom (DOF) motion on a two-dimensional plane. The design of an omnidirectional wheel usually consists on the minimization of the gap between the rollers in order to reduce the generation of vibrations. However, in the scientific literature there are different solutions proposed to absorb vibrations using elastic wheel hubs [1] or adding a suspension mechanism on the whole wheel [2]. At the same time, the development of robotic applications based on 3D printing is gaining popularity due its reasonable cost. For example, Ćurković et al. [3] presented a complete printed four-legged 8 DOF mobile robot platform, and Rubies et al. [4] proposed the implementation of an omnidirectional wheel using 3D printing.

The work presented in this chapter is based on the design and implementation of a non-optimal omnidirectional wheel for the Assistant Personal Robot (APR) presented by Clotet et al. [5]. This human-size mobile robot uses three omnidirectional wheels with an optimized gap which allows free motion control in any direction. This optimal design also has the disadvantage of the high manufacturing cost of the pieces that compose the wheel and despite the optimized gap, the wheel rotation produces vibrations that are amplified through the robot structure causing the robot head vibrate. Moreno et al. [2], improved the mobile robot design by reducing the vibrations generated from the omnidirectional wheels with the inclusion of a passive suspension system. The new contributions of the paper are the evaluation of a non-optimal omnidirectional wheel with a passive suspension system of the APR mobile robots and the use of cheap and standard 3D printing techniques to manufacture the omnidirectional wheels. Additionally, the non-optimal omnidirectional wheel implementation is expected to provide more grip in outdoor non-planar surfaces.

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# Chapter 8

# General discussion of the results

This section summarizes the general discussion of the results obtained in each of the chapters presented in this PhD Thesis.

## 8.1. Implementation of a custom, wearable and compact multi-sensing device

This section discusses the results of the work presented in chapter 4 of this Thesis. The proposal of this paper was the implementation of a compact and small multi-sensing device with the objective to dispose a portable gathering ambient data tool with easy connectivity for industrial or educational purposes.

This device was based on a small electronic board which includes an ARM microcontroller and a BME680 sensor. The BME680 sensor provides temperature, pressure, humidity and gas measurement in a compact LGA package through a SPI communication. The sensor was controlled with a compact ARM microcontroller. The microcontroller was programmed to read periodically the data of the BME680 sensor and store the data in a buffer for fast response. The more challenging task was the implementation of the complex communication required by the sensor. The implementation of an automatic task allowed to send and receive messages between the multi-sensing device and the Host device through a conventional serial port by the implementation of the USB Communication Device Class (CDC). This feature allowed the usage of an open-source software program to communicate with the multi-sensor device.

This device provides access to temperature, pressure, humidity and gas sensor resistance of a multi-sensing device. The portable multi-sensing device was moved between three known areas in order to cause changes in the reading levels of the sensing elements and verify the correct performance of the automatic tasks developed in the microcontroller.

## 8.2. Early gas leak detection using a mobile robot with a low-cost gas sensor array

This section discusses the results of the work presented in chapter 5 of this Thesis. The proposal of this work was the application of a 16 low-cost Metal-Oxide (MOX) gas sensor array combined with a mobile robot as an early gas leak detection tool for safety purposes. The experiments were performed in the corridor on the second floor of the Polytechnic school from the University of Lleida. The mobile robot was equipped with the gas sensor array and a Photo-Ionization Detector (PID) for validation purposes. The robot traversed the corridor using the same trajectory in all the experiments. The gas sources were placed in the middle of the corridor with an odor delivery system.

The first measurement experiments provided a dataset that confirmed that the array sensor device was sensible to ethanol and acetone within their limit of detection (LOD), and to build the Partial Least Square Discriminant Analysis (PLS-DA) classifier. The PLS-DA classifier was validated by capturing the unseen data from the second measurement campaign into the score plot obtained from the dataset of the first measurement campaign. The PLS-DA was able to predict the class converging from air (far from the source) to the corresponding gas source (acetone or ethanol).

The second experiments were developed on four different scenarios for validation purposes. The first scenario proposed a case of a single gas source leak (ethanol or acetone) located in the middle of the corridor with the HVAC of the building switched on. In this case, the detection of the gases appeared just after the robot passed the gas source and the PLS-DA classifier successfully converge in ethanol or acetone gas class. The sensor array reached the peak value at 5 m

from the source which agree with the existence of air recirculation induced by the HVAC system. The second scenario proposed the case of a single gas source leak (acetone) located in the middle of the corridor and the HVAC of the building switched off. Compared with the previous results, the evaporated acetone presents less diffusion due the inexistence of recirculating air in the building. This allows to determine the location of the gas source more precisely. The third scenario proposed the case of two gas sources (ethanol and acetone) placed in different locations of the corridor and the HVAC turned off to avoid the mixture of the two substances. In this case the detection of ethanol or acetone appeared displaced from the gas sources. This displaced detection was probably caused by the natural convection from the difference temperature gradient between the interior (26.5ºC) and exterior (31.4º) of the building. The fourth scenario proposed the case of a single gas source (ethanol) placed inside a laboratory with the door closed and the HVAC turned on. The robot explored the corridor without entering the room although the air recirculation allows the gas to spread outside of the room. In this case the gas sensor array was able to detect the ethanol before and after passing through the door closed. In this case, the PID provided a more accurate detection but only detects when the robot passed in front of the door. The results demonstrated the successfully detection of a gas leak inside a closed laboratory by using mobile robot equipped with an array of MOX gas sensors when the HVAC system of the building was switched on.

## 8.3. Mobile robot self-localization and collision avoidance using a 2D tilted-down LIDAR

This section discusses the results of the work presented in chapter 6 of this Thesis. The proposal of this work was mobile robot self-localization and collision avoidance by using a 2D tilted-down LIDAR. The first set of experiments evaluated the detection capabilities of a 2D tilted-down LIDAR. For this experiments, the 2D LIDAR was tilted down at different angles in order to evaluate the detection capabilities at a different distances. The objects used in this paper for the detection experiments were: a low-height box placed on the ground,

one shoe/leg, stairs going down and stairs going up. In this work a positive threshold of 50 mm over the expected ground height was considered an obstacle and a negative threshold of -50 mm was considered a hole. The result of the experiments verified that a 2D tilted-down LIDAR was able to detect objects and holes. These detection results combined with the minimum distance required to prevent any collision or fall set the tilt angle at 25º, which guarantees the object detection at a frontal distance of 700 mm. This optimal tilted angle was validated by repetitive experiments.

The second set of experiments evaluated the capability of the APR-03 mobile robot to self-locate by a 2D tilted-down LIDAR. For this experiments, the mobile robot was deployed in random locations of the corridor of the facility. The results confirmed that the information obtained by a 2D tilted-down LIDAR can be used to self-locate the mobile robot using the ICP algorithm and the information provided by a 2D map previously obtained with the same 2D LIDAR placed in horizontal. In specific locations, the short-range information provided by the tilted 2D LIDAR can provide worse self-locations results and miscalculate its position. However, in this cases the ICP was able to recover and estimate the path trajectory followed by the mobile robot. Finally, the mobile robot was also deployed close to an area with stairs going down performing pseudo-random displacements. This challenging conditions were overcome avoiding any collision or falling thanks to the methodology proposed by projecting the information obtained of the tilted 2D LIDAR to the horizontal 2D map.

## 8.4. Design, implementation and vibration analysis of a non-optimal omnidirectional wheel

This section discusses the results of the work presented in chapter 7 of this Thesis. The proposal of this work was the design and implementation of a non-optimal omnidirectional wheel. The first experiment evaluates the vibrations generated on the mobile robots APR-01 (without suspension) and APR-02 (with suspension) when using optimal omnidirectional wheels. This experiment was performed as a reference for the next experiments when using the designed non-

optimal omnidirectional wheels. The vibrations were measured with an accelerometer at a floor height of 500 mm (base of the robot) and 1420 mm (head of the robot). The mobile robot performed a forward displacement at 60 m/s during 4 s. The results showed that the accelerations measured in the APR-02 were reduced by 68% relative to the APR-01 when using a passive suspension system.

The implementation of the non-optimal omnidirectional wheel was performed using Polylactic Acid (PLA) as a 3D printing material. The design was tested using two 3D printing configurations, identified as soft rim and hard rim. The final implementation of the omnidirectional wheel was composed of 23 low-cost in-line skate wheels, one rim and one screw. The implemented wheel showed a 30% weight reduction relative to the optimal omnidirectional wheel implemented with aluminum, a 56% reduction of the pieces that compose the wheel and the manufacturing cost was reduced by one order of magnitude.

The next experiment compared the vibrations generated between the optimal omnidirectional wheel, the non-optimal soft rim omnidirectional wheel and the non-optimal hard rim omnidirectional wheel. The measurement module was placed over the DC motor (test without suspension) and on the base of the robot (test with suspension). Then the measurement module applied different PWM values to measure the rotational speed and the accelerations generated. The results showed that (1) the accelerations increases as the rotational speed also increases, (2) the accelerations on the non-optimal wheels in a range up to 60% PWM were similar or slightly higher than the optimal wheel, (3) the vibrations originated on the base of the robot were significantly reduced compared with the vibrations originated over the DC motor thanks to the passive suspension system and (4) the non-optimal hard rim omnidirectional wheel produced similar or lower vibrations than the non-optimal soft rim omnidirectional wheel. The general conclusion led to the proposition of the non-optimal omnidirectional wheel based on a hard rim as an alternative to the optimal omnidirectional wheel used in the APR.

The final experiment performed was proposed to evaluate the APR-02 mobile robot using the proposed non-optimal omnidirectional wheel. The experiment consisted on the measurement of the vibrations at the base and head of the robot.

The mobile robot performed a forward movement at 60 m/s during 4 s. The final comparative showed that (1) the vibrations generated on the base was almost the same when using optimal or non-optimal omnidirectional wheels and (2) the vibrations generated on the head of the APR-02 with non-optimal omnidirectional wheels was 54% lower than APR-01 and a 43% higher than the APR-02 using the optimal omnidirectional wheels.

# Chapter 9

# Conclusions

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This PhD Thesis has addressed the development and improvement of the applications and functionalities of the Assistant Personal Robot platform.

The major achievements of this PhD Thesis have been:

- **Implementation of a custom, wearable and compact multi-sensing device**

  This work has proposed the design, development and implementation of a compact and portable multi-sensing device with temperature, pressure, humidity and gas measurement capabilities. The multi-sensing device consisted on a small electronic board which includes a reduced size microcontroller and a compact multi-sensing device. The work consisted on the software development of several automatic tasks in the microcontroller in order to establish the communications between all the embedded devices. The objective was to develop a portable gathering ambient data tool for research, industrial or educational purposes.

- **Early gas leak detection using a mobile robot with a low-cost gas sensor array**

  This work proposed a gas sensing device embedded on a mobile robot for early gas leak detection. The sensing device was composed by a matrix of 16 low-cost Metal-Oxide (MOX) gas sensors. The custom

board generates 16 voltage measurements, which are converted in to conductance values with a 10-bit ADC. A threshold level was applied on all the measurements as a fast indicator of gas concentration. The conductance values were trained using a Partial Least Square Discriminant Analysis (PLS-DA) classifier for air, ethanol, or acetone detection.

The proposed system was able to successfully detect and classify the different target gases under different HVAC conditions. The main contributions were based on the number of Metal-Oxide (MOX) gas sensors used, the multiple gas sources experimented, the low gas concentrations detected and the complex scenario evaluated. The major achievement of this proposal was the combination of a mobile robot and a low-cost gas sensing device that was able to detect a gas leak produced in a contiguous closed room due to the small leakages under the door induced by the forced ventilation system of the building.

- **Mobile robot self-localization and collision avoidance using a 2D tilted-down LIDAR**

This work proposed mobile robot self-localization and collision avoidance using a 2D tilted-down LIDAR. The first part of the work was focused on different experiments in order to verify the detection performances of a 2D tilted-down LIDAR. The second part was focused on the development of a set of experiments with APR-03 mobile robot performing pseudo-random displacements on different scenarios. The results demonstrated that the mobile robot self-localization with a 2D tilted down LIDAR was possible using a 2D reference map created with a 2D horizontal LIDAR. The major achievement of this proposal was the use of a fixed tilted-down 2D LIDAR for collision avoidance and for mobile robot self-localization without requiring a motorized device to change the tilt of the LIDAR.

- **Design, implementation and vibration analysis of a non-optimal omnidirectional wheel**

  This work proposed the design and implementation of a non-optimal omnidirectional wheel for an APR mobile robot. This work was focused on a comparative analysis of the vibrations generated between optimal/non-optimal wheels and the inclusion of a passive suspension system. The non-optimal omnidirectional wheel implemented showed a 30% weigh reduction, a 56% reduction of the pieces that conforms the wheel and a reduction of one order of magnitude on the manufacturing cost. The experiments evaluated the vibrations generated by the APR-02 using the proposed non-optimal omnidirectional wheels. The results showed that the vibrations measured on the head of the APR-02 with non-optimal omnidirectional wheels was 54% lower than the APR-01 and a 43% higher than the APR-02 using optimal omnidirectional wheels. The results empirically demonstrated that the APR omnidirectional robots were capable to take advantage of their passive suspension system to use the new non-optimal omnidirectional wheels. The major achievement resides on the reduction of vibrations, cheaper manufacturing cost while providing more grip. The implementation of this non-optimal omnidirectional wheels has opened the possibility to deploy new applications of the APR mobile robots in outdoor environments.

# Chapter 10

# Future work

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The main goal of this Thesis has been the development and improvement of the applications and functionalities of the Assistant Personal Robot platform. This section proposes some ideas and concepts that can be addressed as future work:

**a) Improvements of new control boards**: Future works can be focused on the development of new electronic boards accordingly the new functionalities of the mobile robot. This boards must include additional sensing devices, control of the connection/disconnection of the electronic boards, interface to other devices such as thermal cameras, etc. Currently, the incorporation of new sensors and actuators require individual electronic boards specialized in one unique task and this devices require additional simplification and aggrupation. Additionally, the new electronic control board must be able to measure the electrical energy consumption of the mobile robot and predict the energy consumption required to perform some tasks.

**b) Experimentation and validation in domestic scenarios**: Future works can be focused on the experimentation and validation of the new tools developed in this Thesis in domestic scenarios. In this direction, future work must be focused on improving the recognition of user activity in domestic scenarios.

**c) Development of a new APR mobile robot focused on operate outdoors**: The development of the new non-optimal omnidirectional wheel has opened the possibility to operate outdoors. Future work can be focused on the development of

new mobile platforms optimized to take full advantage of the proposed non-optimal omnidirectional wheel on rough indoor and outdoor unstructured floors.

# Nomenclature

| | |
|---|---|
| **A*** | A-star "search algorithm" |
| **AAL** | Ambient Assisted Living |
| **ADC** | Analog-to-Digital Converter |
| **AmI** | Ambient Integillence |
| **APR** | Assistant Personal Robot |
| **ARM** | Advanced RISC Machine |
| **CAD** | Computer Aided Design |
| **CAM** | Computer Aided Manufacturing |
| **CDC** | Communication Device Class |
| **CNC** | Computer Numerical Control |
| **DC** | Direct Current |
| **DDR4** | Double Data Rate 4 |
| **FCU** | Fan Coil Unit |
| **FFF** | Fused Filament Fabrication |
| **GDM** | Gas Distribution Mapping |
| **GSL** | Gas Source Localization |
| **HVAC** | Heating Ventilation and Air Conditioning |
| **I2C** | Inter-Integrated Circuit |
| **ICP** | Iterative Closest Point |
| **IIR** | Infinite Impulse Response |
| **IoT** | Internet Of Things |
| **IQR** | Interquartile Range |

| | |
|---|---|
| **IT** | Information Technology |
| **LED** | Light Emitting Diode |
| **LGA** | Land Grid Array |
| **LIDAR** | Laser Imaging Detection And Ranging |
| **LOD** | Limit Of Detection |
| **LV** | Latent Variables |
| **MOX** | Metal-Oxide |
| **MRO** | Mobile Robotic Olfaction |
| **NVMe** | Non-Volatile Memory Express |
| **OTG** | On-The-Go |
| **PCIE** | Peripheral Component Interconnect Express |
| **PID** | Photoionization Detector |
| **PLA** | Polylactic Acid |
| **PLS-DA** | Partial Least Squares Discriminant Analysis |
| **PnP** | Plug And Play |
| **ppb** | Parts per billion |
| **ppm** | Parts per million |
| **PWM** | Pulse Width Modulation |
| **RAM** | Random Access Memory |
| **RISC** | Reduced Instruction Set Computer |
| **SLAM** | Simultaneous Localization And Mapping |
| **SMD** | Surface Mounted Device |
| **SPI** | Serial Peripheral Interface |
| **SRAM** | Static Random Access Memory |
| **SSD** | Solid State Drive |

| | |
|---|---|
| **STL** | Standard Triangle Language |
| **SWD** | Serial Wire Debug |
| **UART** | Universal Asynchronous Receiver-Transmitter |
| **UAV** | Unmanned Aerial Vehicles |
| **USART** | Universal Synchronous And Asynchronous Receiver-Transmitter |
| **USB** | Universal Serial Bus |
| **VOC** | Volatile Organic Compound |