Universitat de Lleida

Improving the quality of life of older adults and people with reduced mobility through an Assistant Personal Robot

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TESI DOCTORAL

Improving the quality of life of older adults and people with reduced mobility through an Assistant Personal Robot

Eduard Clotet Bellmunt

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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El Dr. Jorge Palacín Roca, professor Titular de l'Escola Politècnica Superior de la Universitat de Lleida.

CERTIFICA:

Que la memòria "Improving the quality of life of older adults and people with reduced mobility through an Assistant Personal Robot" presentada per Eduard Clotet Bellmunt per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, 31 de gener de 2019.

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Resum

En aquesta memòria es presenten els diversos treballs realitzats en l'àmbit de la robòtica assistencial mitjançant el desenvolupament i millora del robot assistencial APR (Assistent Personal Robòtic) i les seves aplicacions en entorns reals.

L'increment en l'esperança de vida de les persones ha propiciat un creixement de la població amb edat superior als 65 anys (població anciana). En l'actualitat, garantir una assistència digna a aquest sector de la població ha esdevingut un problema crític, essent considerat un dels principals problemes de salut pública en països desenvolupats; malauradament, les expectatives de futur no resulten tranquil·litzadores. Recents estudis realitzats durant els últims anys pronostiquen un increment important de la població anciana, agreujant el problema de l'assistència a la tercera edat. Donades aquestes circumstancies resulta de vital importància el desenvolupament i automatització de nous sistemes d'assistència que permetin fer front a aquest problema.

En aquesta memòria es presenten els treballs realitzats amb els dos models de robot assistencial APR fets a la Universitat de Lleida. El robot APR-01 va ser dissenyat originàriament per oferir serveis de telepresència per tal de millorar la comunicació remota al domicili entre familiars, personal assistent, personal mèdic i persones grans o amb discapacitat. El robot APR també té aplicació en integració laboral i social de persones amb mobilitat reduïda, oferint una plataforma robòtica mòbil que pot ser utilitzada en qualsevol lloc que disposi d'una connexió a internet. Seguidament es presenta el desenvolupament i avaluació d'una aplicació dedicada a la millora de la mobilitat de persones grans o amb mobilitat reduïda mitjançant l'ús de la plataforma robòtica APR-02 en forma de caminador motoritzat intel·ligent. El sistema proposat inclou un algoritme que realitza una correcció automàtica de la trajectòria del robot mòbil per tal de millorar el confort i eficiència durant els desplaçaments. Finalment, es proposa l'ús de les capacitats de navegació autònoma del robot APR-02 per tal d'analitzar i detectar condicions ambientals potencialment perilloses tals com la falta de il·luminació o nivells inapropiats d'humitat en entorns domèstics i institucionals.

Resumen

En esta memoria se presentan los múltiples trabajos realizados en el ámbito de la robótica asistencial mediante el desarrollo i mejora del robot asistencial APR (Asistente Personal Robótico) y sus aplicaciones en entornos reales.

El incremento en la esperanza de vida de las personas ha propiciado el crecimiento de la población cuya edad supera los 65 años (población anciana). En la actualidad, garantizar una asistencia digna a este sector de la población se ha convertido en uno de los principales problemas de salud pública en países desarrollados. Desafortunadamente, las expectativas de futuro no resultan esperanzadoras. Recientes estudios realizados durante los últimos años auguran un incremento importante de la población anciana, agravando el problema de la asistencia a la tercera edad. Dadas estas circunstancias resulta de vital importancia el desarrollo y automatización de nuevos sistemas de asistencia que permitan hacer frente a este problema.

En esta memoria se presentan los trabajos realizados con los dos modelos de robot asistencial APR creados en la Universidad de Lleida. El robot APR-01 fue diseñado originariamente para ofrecer servicios de tele-presencia con el objetivo de mejorar la comunicación remota en el domicilio entre familiares, personal médico, y personas mayores o con discapacidades. El robot APR también tiene aplicaciones en la integración laboral y social de personas con movilidad reducida, ofreciendo una plataforma robótica móvil que puede ser utilizada en cualquier lugar que disponga de conexión a internet. Seguidamente se presenta el desarrollo y evaluación de una aplicación dedicada a la mejora de la movilidad en personas mayores o con movilidad reducida mediante el uso de la plataforma APR-02 como andador motorizado inteligente. Esta propuesta incluye un algoritmo de corrección automática de la trayectoria del robot móvil para mejorar el confort y la eficiencia de los desplazamientos. Finalmente se propone el uso de las capacidades de navegación autónoma del robot APR-02 para analizar y detectar posibles condiciones ambientales potencialmente peligrosas tales como la falta de iluminación o niveles inadecuados de humedad en entornos domésticos e institucionales.

Summary

This memory presents the multiple works performed in the field of assistive robotics through the development and improvement of the assistive robot APR (Assistant Personal Robot) and its applications in real scenarios.

The increasing human life expectancy is fostering the growth of the population aged over 65 years old (elderly population). At this day, providing an appropriate assistance to this sector of the population is considered as one of the main public health concerns in developed countries. Unfortunately, the expectations for the future are far from reassuring. Recent studies in human population stated that the number of older adults is expected to grow in years to come, worsening the problem of providing appropriate assistance to them. Due to this expectations, the development of new and automatized assistive methods to cope with the presented problem is to be considered a major priority.

This memory presents the multiple works performed with the two models of the assistive robot APR developed by the University of Lleida. The APR-01 was conceived to offer telepresence services with the objective of improving the communication between dependent people in their homes (older adults and people with disabilities) and relatives or medical staff. The APR robot can also be used to improve the social integration of people with mobility impairments, offering a mobile robotic platform that can be deployed in any location with an internet connection. The second project developed during this thesis consisted on the design, implementation and evaluation of an application embedded in the APR-02, allowing it to be used as a smart, motorized walker to improve the mobility capabilities of its user. The presented solution includes the implementation of an automated trajectory correction system that performs adjustments to the path followed by the robot, maximizing the comfort and efficiency of the displacements. Finally, the use of the autonomous robot APR-02 as an ambient monitoring tool is presented. The objective of this last work is to analyze and detect potentially harmful ambient conditions such as poorly illuminated areas or inadequate humidity levels.

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Chapter 1

Introduction

1.1. An ageing society

1.1.1. Introduction

An aged society consists on a shift of the median age of the population towards older ages, indicating that the proportion of young people over older adults has decreased. Figure 1.1 shows the evolution of the median age in the six continents of the world during the last seven decades, highlighting the fact that world population is ageing. This trend was firstly noticed in developed countries, although developing countries are also starting to reproduce this phenomena.

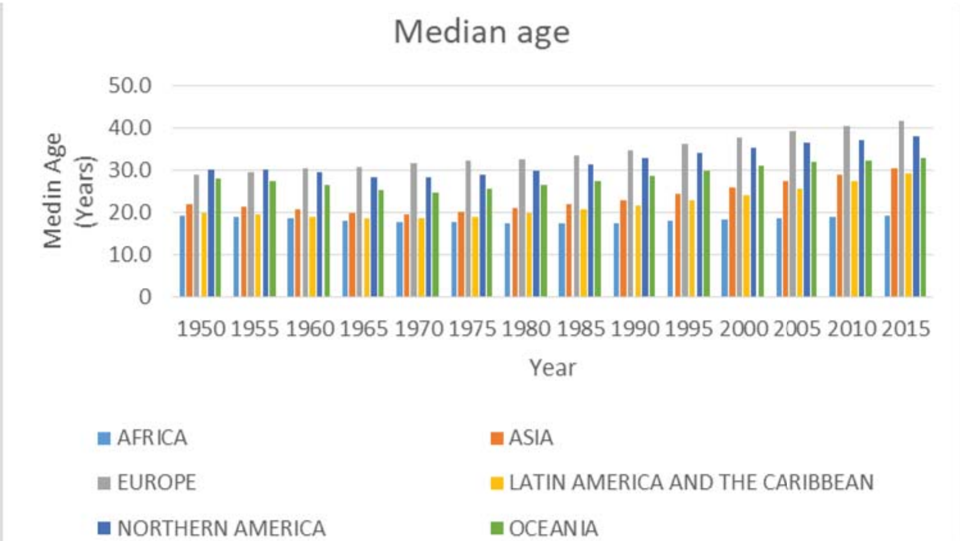

Fig. 1.1. Evolution of the median age of the world population by continents (data source [1]).

1.1.2. Analysis of the causes

According to the 2017 report from the United Nations [2] two main factors are responsible for the increase of the ageing population: lower fertility rates, and longer life expectancies. The decrease in fertility rates implies that a lower number of kids are born each year, increasing the gap between the proportion of young/aged people. Fig. 1.2 shows the number of births a woman was expected to give according to the fertility rates of each continent during a specific time period. Fig. 1.2 shows that Asia and Latin America were the continents that experienced the highest decrease in fertility rates during the last decades (61.98% and 63.53% respectively), while Africa (28.62%) and Oceania (37.18%) were the most stable.

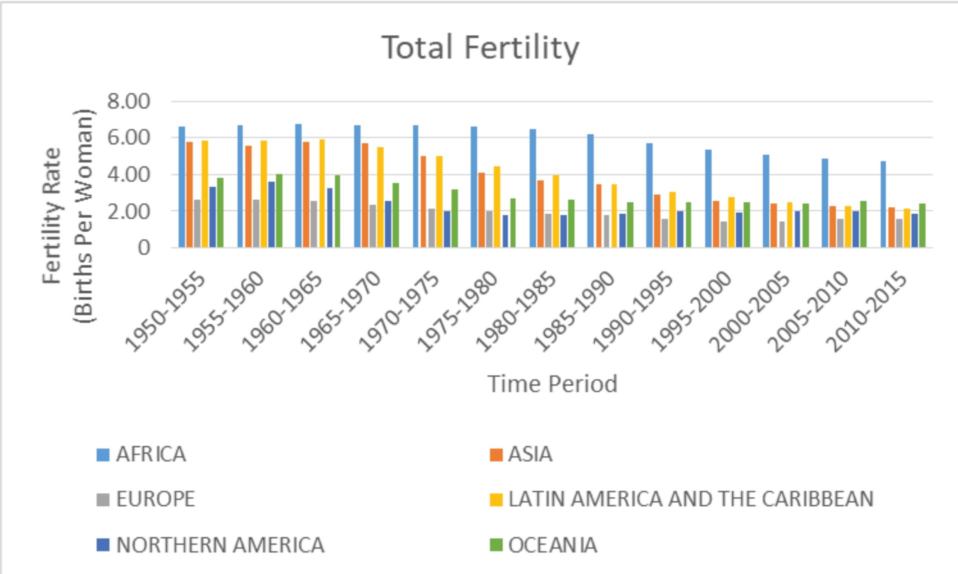

Fig. 1.2. Evolution of the total fertility of the world population as expected life births per mother during the specified period (data source [3]).

Life expectancy represents the number of years a person is expected to live at the time of its birth. Fig. 1.3 shows the evolution of life expectancy by continents. Life expectancy has been gradually increasing during the last seven decades due to improvements in sanitation, education, and medical advances; one of the most contributing factors was a drastic decrease in child mortality along with better survivability rates at young ages [4]. Figure 1.3 also shows that the life expectancy differences between continents is becoming smaller each year. Proof of that is that the mean life expectancy in 1950-1955 was of 54.17 years at the time of birth, with a standard deviation between continents of 12.52 years, while in 2010-2015 the mean life expectancy was 73.50 years at the time of birth, with a standard deviation of 7.02 years.

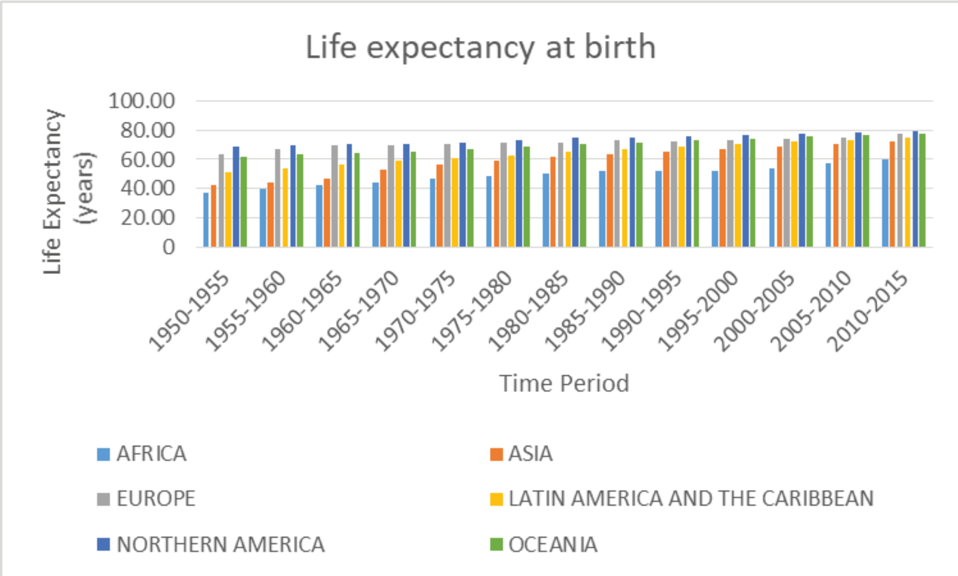

Fig. 1.3. Evolution of the life expectancy at the time of birth of world the population (data source [5]).

1.1.3. Consequences and long-term expectations

One of the main consequences of this improvement over life expectancy and the reduction of fertility rates is that the world population is rapidly ageing. The existing gap between young and old population has grown considerably during the last years. Although this mostly affected to the developed countries, developing countries are expected to follow the same trend in years to come. This has caused an increase of the dependency ratio between people in their active ages (20-64 years old) and older adults (aged over 64 years old), meaning that the number of people that can provide assistance to elderly people is becoming lower each year. The evolution of the dependency rates of the world population by continents since 1950 is presented in Fig. 1.4, showing that Europe, Northern America, and Oceania have been the most affected continents, reaching a current dependency rate of 28.6, 24.8, and 20.9 respectively. Asia and Latin America presented a similar evolution through the past years, showing a low but constant increase in dependency rates. Finally, Africa has almost maintained the same dependency ratio since 1950.

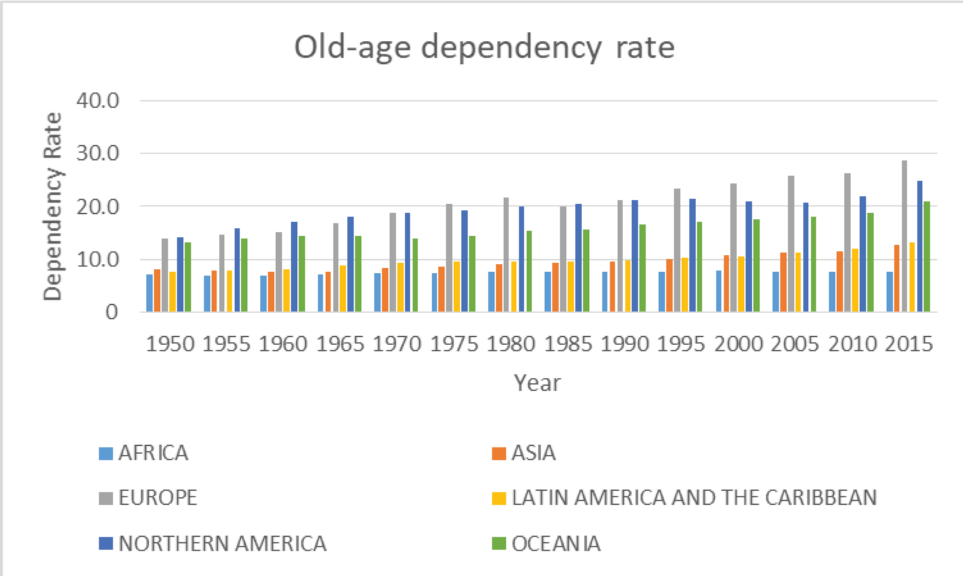

Fig. 1.4. Evolution of the dependency rate for people aged over 64 years old (data source [6])

The expectations for the future prognosticate that the dependency rates will keep increasing, mainly due to the current trend of low birth rates. The United Nations report from 2017 [2] indicates that the birth rate in developed countries is expected to be reduced 20 percent by the end of the century, while in less developed countries this percentage will raise just over 51 percent. In 2100 the number of older adults aged above 80 years old is expected to be seven times larger than in 2013, and 20.1 million people will reach the 100 years old.

1.2. Quality of life in older adults

1.2.1. Introduction

Providing a dignified and efficient assistance to elderly people aged over 64 years old has become one of the main health concerns in most of developed countries. Finding newer and safer methods to assist elderly people will become vital to face this challenge in years to come.

Being able to maintain a safe and independent life is one of the main factors that will define the quality of life of older adults. Recent studies indicate that physical activity has a positive impact in both physical and mental health [7]. This becomes particularly important since the physical capabilities of older adults are known to deteriorate over time due to a sedentary lifestyle. Additionally, the results presented in [8] concluded that physical activity is associated with a lower risk of mortality in elderly people, thus physical activity should be performed in nursing homes and geriatric residences.

Mental health also plays an important role in the quality of life of older adults. Although it is widely accepted that depression is relatively common in elderly people, the lack of a concise definition for depression and accurate methods to measure it makes it difficult to determine the prevalence of this mental illness in older adults [9]. A study performed by Amy Fiske et al. identified a correlation between depression and other clinical conditions such as cardiovascular diseases, diabetes, dementia, anxiety and insomnia among others [10].

Finally, it is important to design and deploy appropriate solutions that fit the needs of the user, maximizing its acceptance. The study presented in [11] showed that the acceptance towards the use of assistive services and devices can be positively influenced by relatives, friends and professional caregivers. As an example, the acceptance of using wearable fitness trackers in a group of 30 adults with chronic illness was performed in [12]. Results showed that the presented solution had a high level of acceptance among the users, who also felt more inclined to perform physical activity as they were able to measure their progress through the data gathered by the fitness wristband.

1.2.2. Physical safety

Although the existence of nursing homes and geriatric residences, a large number of older adults are reluctant to leave their homes, mostly due to the fact that risk perception by elderly people tends to be misjudged [13]. Risk perception plays an important role in domestic safety. In [14] a set of observations over a group of 36 hospitalized older adults is performed to evaluate their risk perception. Results showed that most of them were aware of the consequences of falling, but decided to proceed with the activity anyway. Some of the nurses involved in the experiment stated that even wearing an alarm necklace, some of the elderly people felt confused and disoriented after experiencing a fall, being unable to press the alarm button.

One of the main drawbacks of user-activated alarm devices is that after experiencing a fall the injured person may not be able to request assistance by himself. For this, some solutions propose the integration of sensors that monitor external parameters to detect domestic falls, allowing the device to automatically produce an assistance request. The first platforms that implemented this solution were smartphones. The main motivation for this is that users tend to take their smartphone with them all the time. Additionally, smartphones provide easy access to an accelerometer, a sensor used to detect the acceleration changes applied to the device. One of the first examples of the use of a smartphone as a fall detection method is presented in [15].

The popularization of the concept of Internet of Things (IoT) and Ambient Intelligence (AmI) fostered the development of WSN-based solutions, aimed to create less intrusive monitoring methods to be deployed in domestic environments and geriatric institutions. In 2016 Toni et al. presented CIUDATS, a monitoring solution deployed in a health care facility [16]. One of the features provided by their system was the use of several RFID readers and RF beacons distributed along the facility. The system allowed to track and monitor the patients through a wristband equipped with an RF transmitter.

1.2.3. Mental health

Although multiple factors are considered relevant instigators of depression in older adults, the presence of chronic illness [17] and social isolation [18] are thought to be the main causes.

The popularization of IT (Information Technologies) is providing a new and accessible platform to design and deploy communication solutions that can improve social interaction for people with mobility problems and older adults. An interesting approach to minimize the impact of loneliness among elderly people is presented in [19]. In this work, the adoption of social media to improve the quality of life in elderly people proved to be successful, although empirical experimentation is yet to be conducted. In [20] a telepsychiatry service was implemented. During the experiment, a total of 134 sessions with patients that presented one or multiple mental disorders were performed. Results showed that although the low feedback provided by the users themselves, the overall attitude of those who shared their opinion was positive (88.2 % to 98 %).

1.3. Assistive robots

1.3.1. Introduction

The advances in the field of robotics achieved during the last decades have fostered the inclusion of robots in fields that were previously only meant to be performed by humans. The pursue for newer and better ways to provide assistance to elderly people is becoming particularly challenging due to the high dependency ratios caused by a rapidly ageing society. The incorporation of robotics in this field can become a feasible solution for this problem.

1.3.2 Assistive robots in real environments

Although at this date it is impossible to remove the need of human expertise and assessment in assisting elderly people and their needs, robotics can be used to provide a certain degree of automatization in the process of monitoring the user well-being and safety.

The inclusion of this type of robots in geriatric residences and health care centers is gaining popularity. In [21] a telepresence robot was deployed in a retirement center located in south central Ohio. The objective of this work was to assess the degree of usability and acceptability of the mobile robotic platform in a realistic environment. The results obtained through the questionnaires proved that the use of a telepresence robot in such environment was perceived as positive by both the assisted and the caregivers; nevertheless, the deployed robot experienced some technical issues during its duty, highlighting the fact that this technology still needs to be improved before being reliable enough to be introduced in unsupervised scenarios. An additional example of assistive robots in nursing homes is provided in [22], where the mobile robotic platform "Pearl" was used to guide and assist elderly people in a nursing home. The main objective of this robot was to provide guidance across the institution, but it was also capable of performing additional tasks such as: reminding users of medical appointments, request assistance, announce the current date and time, and to check the presence of a user in specific locations.

Although being less common, the integration of assistive robots in houses is also being studied. An example of the use of a mobile robot in a domestic environment is presented in [23], where the mobile robotic platform "Hobbit" (Fig. 1.5) was deployed during multiple weeks in several homes inhabited by older adults. The presented robot was equipped with an RGB-D camera to detect domestic falls and to assess different potential fall-related threats in the house. Results showed that the "Hobbit" robot was capable of detecting if a person was laying on the ground, pick up objects and place them in the desired location, and to detect gestures performed by the users for human-robot interaction.

Fig. 1.5. Image of the Hobbit robot [24].

Finally, the acceptance of the use of a mobile robot for assistive purposes is presented in [25]. The study was performed in order to evaluate the satisfaction and acceptance degree of six “Robot-Era” mobile robots in a group of 35 participants in three different environments: indoor, outdoor and condominium. Results showed a high acceptance level in the three presented scenarios (73.04% in domestic environments, 76.85% in condominium environments, and 75.93 % in outdoor environments).

1.4. The APR platform

1.4.1. Introduction

The Assistant Personal Robot (or APR for short) is a multipurpose mobile robot designed and implemented by the Signal Processing and Robotics Research Group from the University of Lleida. One of the main objectives of the APR is to provide assistance to older adults and people with mobility impairments in domestic environments and institutions, but additional tasks such as monitoring environmental conditions and surveillance can also be performed.

Although two versions of the APR robot will be used during the development of the presented work (APR-01 and APR-02), some features are common in both versions: use of omnidirectional wheels in a kiwi distribution (three omnidirectional wheels shifted 120 degrees), humanoid shape, powered by three 12Ah sealed lead acid batteries located at the base of the robot, onboard 2D LIDAR sensor, and the use of a tactile screen as a human-robot interface.

The use of omnidirectional wheels (Fig. 1.6) provide high mobility capabilities to the robot. This is especially important when operating in domestic environments due to the low maneuvering space. This holonomic motion system allows the robot to rotate over its vertical axis and to move in any direction by controlling the power applied to each one of the three motors that drive the omnidirectional wheels. The design and validation process of this motion system is presented in [26].

Fig. 1.6. Image of the internal structure of one of the omnidirectional wheels used in the APR robot.

A LIDAR (Light Detection and Ranging) sensor is a device designed to provide a two dimensional point cloud representation of its surroundings. The main principle of function is based on measuring the time of flight of an infrared pulse (time between the transmission of the IR pulse and reception of its echo) in order to determine the distance between the sensor and the nearest solid object in the projected direction. This is performed in multiple angles in order to obtain a representation of the layout around the sensor. Both robots are equipped with a 2D LIDAR sensor. Fig. 1.7-a shows a representation of the area scanned by the LIDAR sensor; Fig. 1.7-b displays the data retrieved by the sensor in millimeters. This information will be used to avoid collisions and for the autonomous navigation procedure of the APR-02.

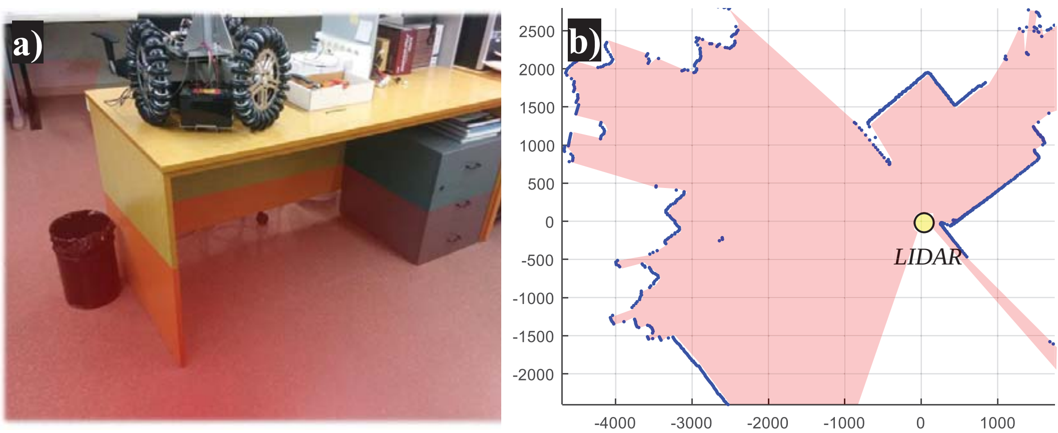

Fig. 1.7. a) Depiction of the area scanned by the LIDAR sensor. b) Visual representation of the 2D point cloud retrieved by the sensor.

1.4.2. APR-01

The APR-01 (Fig. 1.8) is the first model of Assistant Personal Robot. The objective of this initial version is to provide a tele-operated mobile robotic platform that can be deployed in any location with a wireless internet connection. This robot is designed to offer telepresence services to assist elderly people in their homes, although it can also be used to provide a deployable mobile robotic platform for people with reduced mobility, allowing them to interact with the society from the comfort of their home through the robot.

Fig. 1.8. Friends maintaining a conversation through the APR-01 via Skype.

The main computational unit of this robot is an Android tablet located at the head of the robot, providing easy access to all its sensors and wireless connection capabilities. The front camera of the robot is equipped with a wide-angle lens in order to improve the field of view of the operator controlling the robot. Additionally, the head of the robot is equipped with two motors, allowing it to perform pan and tilt adjustments (two DoF). This is particularly important to improve the control of the robot in complex or narrow spaces, allowing the operator to observe the base of the robot and its surroundings without the need of rotating the entire structure.

Finally, each one of the arms of the APR-01 robot is driven by a DC motor that can be controlled by the operator. The main goal of the arms is to provide a limited but yet useful way of interacting with the environment of the robot. As an example, the operator can use the arms of the robot to point directions and objects, knock on doors, and raise its hand to get attention. An additional feature for the APR is presented in [27], where an additional arm is mounted onboard the robot, allowing it to navigate through closed but non-locked doors.

1.4.3. APR-02

The APR-02 (Fig. 1.9) is the second generation of the Assistant Personal Robot, and is conceived as the improved version of the first APR model. This newer version is designed to correct the main flaws detected during the development and evaluation stage of its predecessor.

Fig. 1.9. The APR-02 robot navigating through the corridor.

One of the main features of the APR-02 is its autonomous navigation capabilities (Fig. 1.10), minimizing the limitations of requiring an operator in order to be deployed in any scenario. To withstand the computational demand required to perform autonomous tasks, the robot is equipped with a high-end desktop computer mounted inside the base of the robot. The use of a computer also provides compatibility with a wide range of USB-connected devices and sensors that can be mounted over the robot for ambient monitoring purposes.

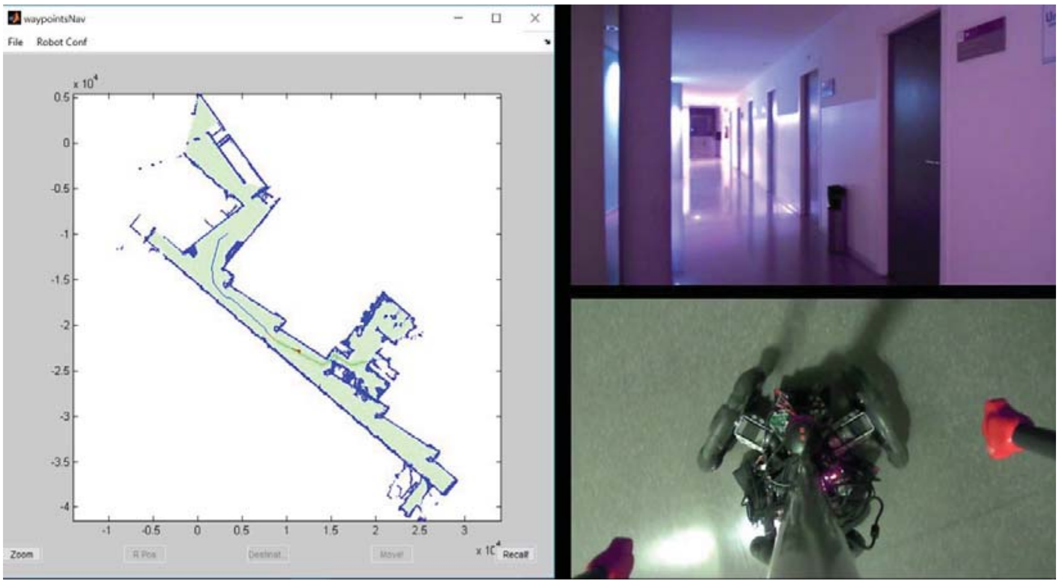

Fig. 1.10. APR-02 performing an autonomous navigation service along the second floor of the Polytechnic School from the University of Lleida.

Another improvement over the previous version of the robot is the implementation of a passive suspension system that reduces the vibrations originated at the base of the robot and transmitted through the entire structure due to its stiffness, which is a common problem found in tower-typed designs. Reducing the vibrations of the APR-02 is especially important as it is expected to carry delicate and expensive sensors in the future. The implementation and evaluation of the suspension system is presented in [28].

Finally, the dc motors used to control the arms of the previous version are replaced by digital servo-motors, increasing the precision of the movements and providing additional information that will be later used to perform the guiding system presented in chapter 5.

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Chapter 2

Objectives

The main objective of this thesis is to improve the quality of life in older adults and people with limited mobility through the design, implementation and evaluation of the mobile robotic platform APR and its features. For this, the presented work is aimed to improve the currently available solutions to four different problems: assistance in older adults in their domestic environment, social integration of people with mobility impairments, mobility in older adults and people with physical disabilities, and the monitoring and detection of potentially harmful ambient conditions in both domestic and institutional environments.

The specific objectives of this thesis are:

1. The development of a remote control system for the mobile robotic platform APR-01. The objective of this system is to provide an easy-to-deploy tool for assisting older adults in their home, and to offer telepresence mobile robot for people with mobility impairments. The requirements of this tele-presence system are: allow remote operation of the APR robot, user-friendly interface, bidirectional audio and video transmission, connectivity in WAN, collision avoidance, detection of network problems, safety protocols, and adaptability to the network capabilities.

2. Design and evaluate a walk-helper application embedded in the APR-02. This application will be aimed to improve mobility in older adults and people with reduced mobility in a real scenario through the use of

the APR-02 as an intelligent motorized walker. Additionally, an automated trajectory adjustment procedure will also be implemented and tested.

3. Design and evaluate an autonomous ambient monitoring tool embedded in the second generation of the Assistant Personal Robot. The developed solution must be able to: navigate autonomously in a real environment, monitor ambient conditions such as temperature, illuminance and humidity, store the coordinates at which each value has been obtained, produce a map of the area displaying the data gathered, and to produce an automated report of the ambient conditions that are considered as inadequate.

Chapter 3

PhD Thesis structure

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 Recercaixa 2013 research grant and the University of Lleida (ajut per a personal predoctoral de la UdL en formació). This PhD Thesis is structured in four chapters corresponding to the four papers presented (three accepted and one under review). According the Scimago Journal Rank (SJR), the paper "Assistant Personal Robot (APR): Conception and Application of a Tele-Operated Assisted Living Robot" is published in a Q1 journal. The paper "Automatic supervision of temperature, humidity, and luminance with an Assistant Personal Robot" is published in a Q2 journal. The paper "Preliminary application of an Assistant Personal Robot as an ambient monitoring tool" is published in a journal with a CiteScore of 0.40. The last paper "Extending the application of an Assistant Per-sonal Robot as a walk-helper tool for people with reduced mobility" is currently under the process of revision in a Q2 journal. Figure 3.1 shows the structure of the PhD Thesis.

The referenced papers are:

- Clotet, E.; Martinez, D.; Moreno, J.; Tresanchez, M.; Palacín, J. Assistant Personal Robot (APR): Conception and Application of a Tele-Operated Assisted Living Robot. *Sensors* (SJR as Q1 in Electronical and Electronic Engineering) **2016**, 16(5), 610.

- Clotet, E.; Martinez, D.; Moreno, J.; Tresanchez, M.; Palacín, J. Preliminary application of an Assistant Personal Robot as an ambient monitoring tool. *Advances in Intelligent Systems and Computing* (0.40 CiteScore) **2017**, 615, 25-31.
- Palacín, J.; Clotet, E.; Martinez,D.; Moreno, J.; Tresanchez, M. Automatic supervision of temperature, humidity, and luminance with an Assistant Personal Robot. *Journal of Sensors* (SJR as Q2 in Electronical and Electronic Engineering) **2017**, Article ID 1480401.
- Palacín, J.; Clotet, E.; Martínez, Dani; Martínez David; Moreno, J. Extending the application of an Assistant Per-sonal Robot as a walk-helper tool for people with reduced mobility. *Senosrs* (SJR as Q2 in Electronical and Electronic Engineering) Submitted.

The four different chapters presented in this work are aimed to provide a solution for different problems that have a negative effect in the quality of life of older adults and people with mobility impairments. For this, the use of the assistive robot APR (Assistant Personal Robot) is proposed. The first work (chapter 4) presents the development of a remotely operated robot that can be deployed to provide assistance to elderly people, and also to be used as a telepresence system for people with mobility impairments. The work presented in chapter 5 presents the development of a walker-helper functionality embedded in the APR-02 robot; its main goal is to improve the balance of the users during displacements in order to prevent domestic falls. The work presented in chapters 6 is designed to create a mobile robotic platform that can monitors the ambient conditions found during autonomous explorations in a known environment. Finally, a system that automatizes the generation of reports that identify inadequate ambient conditions is presented in chapter 7.

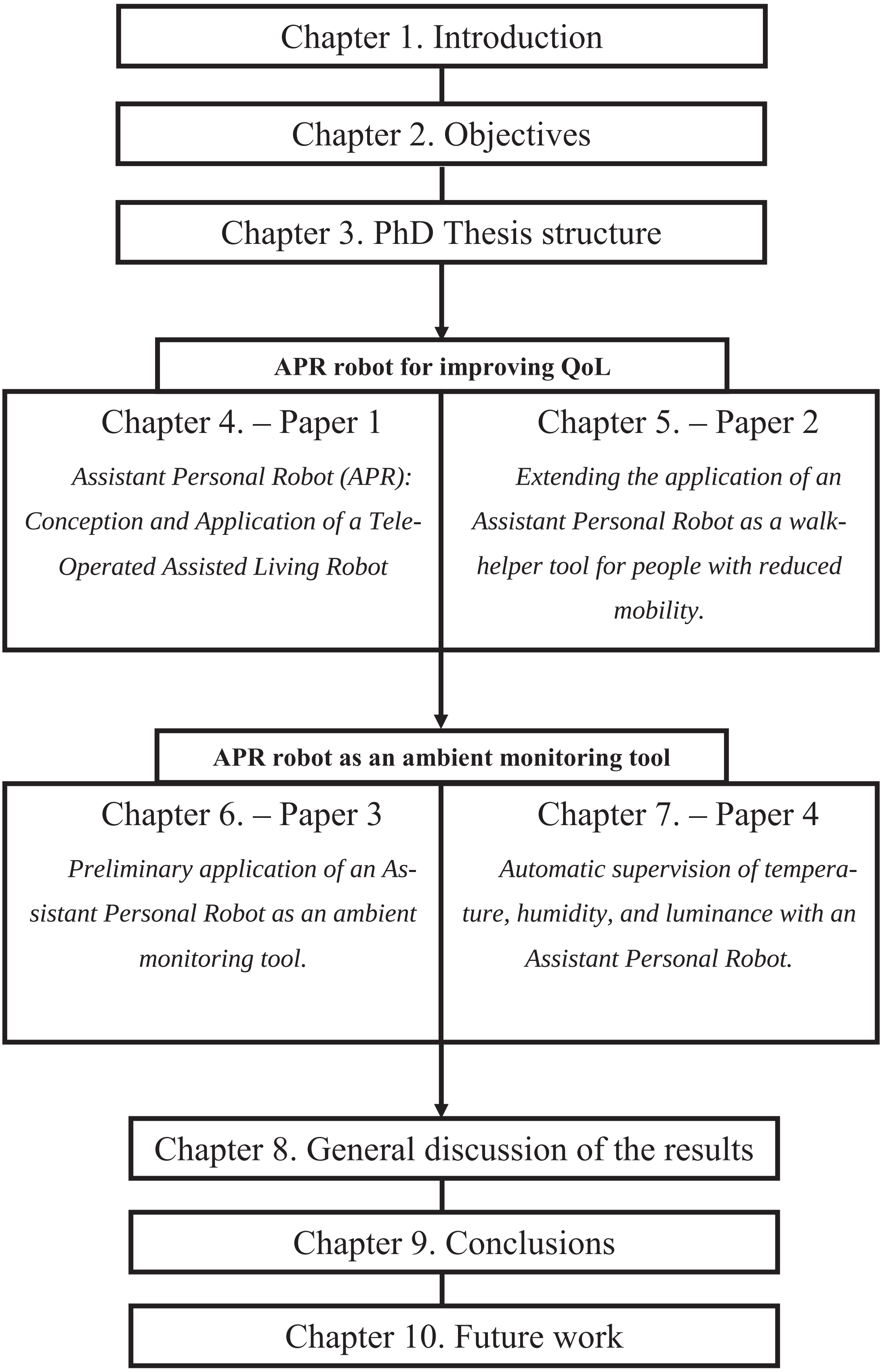

Fig. 3.1. PhD Thesis structure

Chapter 4

Design and implementation of the first-generation Assistant Personal Robot (APR)

4.1. Introduction

The decrease in fertility rates and child mortality, along with the advances in education and health-related fields such as medicine, sanitation, and strict alimentary regulations is prompting the growth of an aged population in developed countries [1,2]. Being able to provide a dignified assistance to this increasing section of the population has become one of the main public health concerns, a problem that is only expected to worsen in years to come due to the increasing gap between the mean active population (ages between 20-64 years old), and elderly people (aged over 64 years old). The need of finding new ways to provide assistance to this part of the population is now a priority for many research groups around the globe, working together in an attempt to find feasible solutions to the constantly increasing dependency rates. Additionally, achieving the complete social integration of people with both psychological and physical disabilities in developed countries is high on the agenda, prompting the research of new ways to minimize the effects that their disabilities have in their daily life.

The Assistive Personal Robot (APR for short) is a humanoid mobile robotic platform created with assistive purposes. The main objective of the APR is to tackle the main problems faced by elderly people (loneliness, home safety, memory loss and sedentary lifestyle) [3,4] and people with mobility impairments (integration, social interaction, and mobility) [5]. To achieve these objectives the APR robot needs to fulfil the following requirements: fluid indoor navigation, safety, high mobility, long-range control system and bidirectional communications, and deployment of built-in applications. For this, the APR robot is equipped with a high mobility system based on three omnidirectional wheels, a 2D LIDAR sensor to prevent collisions, and an Android tablet for wireless communication and human-robot interaction.

The development of the APR robot can be divided in three main fields: electronics, mechanics and programming. This chapter is aimed to provide an in-detail description of the development of the first prototype of the Assistive Personal Robot. The main contribution of the author of this thesis to this work is the design and implementation of the control system used to remotely operate the robot.

4.2. Contributions to the state of the art

The use of robots for assisting elderly people in nursing homes is far from a new concept. As an example, [6] analyses the results obtained when introducing “Pearl”, a guiding robot into a geriatric institution. Another example of the benefits of using a robot in a nursing home is presented in [7], where the robotic platform “Giraff” was used to provide video-conference services between patients with dementia and family members, concluding that long-term residents were more emotionally stable and positive during the calls when compared to other communication methods. One of the main reasons that motivates this work is that most of the above presented assistive robots are conceived as a software solution embedded into already existing robotic platforms, also relying on proprietary software (usually Skype) as their main videoconference solution.

This work presents an in-depth description of the development of the first generation APR robot, completely built and programmed from scratch in order to fulfil the requirements of an assistive robot without the limitations of relying on generic robotic platforms or proprietary software.

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Chapter 5

Development of a walk-helper functionality for the APR-02 robot to improve mobility in older adults and people with mobility impairments

5.1. Introduction

This chapter presents the developments of an embedded application designed for the second generation of APR robot (APR-02), aimed to enhance mobility of elderly people and people with mobility impairments.

Each year 28% to 35% of older adults aged over 65 will experience a domestic fall, this percentage rises up to 50% at ages over 85 years old [1]. This problem is largely worsened by the fact that elderly people tend to underestimate the effects that the aging process has on their ability to move and maintain their balance [2,3]. Studies also showed that after the first accident, elderly people have a 60% probability of experiencing additional falls within the next year [4 5].

Mobility is one of the most important factors required to maximize the Quality of Life (QoL) of older adults [6, 7], allowing them to maintain an independent and dignified lifestyle. Although the widely available number of handheld walking devices such as walking sticks and walkers, the pursue of newer and safer devices that improve mobility for elderly people and people with mobility disorders through better mechanical and automated designs has been on the rise for more than two decades [8, 9]. As an example, in 1996 Shinji Kotani et al. designed a motorized wheelchair that was capable of providing automated guidance to visually impaired people [10].

The objective of the presented work is to develop an additional functionality embedded into the multipurpose robotic platform APR-02 to enhance mobility of elderly people by helping them to maintain their balance during displacements. To achieve this objective, the robot takes advantage of its weight distribution, height and shape, using its arms to provide a stable structure to which the users can hold on to.

The walk-helper mode is enabled by holding the arms of the robot at its back, at a height that the user feels comfortable. After three seconds the APR-02 robot will engage the walker-helper mode. Once enabled, the maximum speed of the robot is drastically reduced, helping the user to follow the robot in safe conditions. At this point, the user can control the direction of the displacements performed by the robot by changing the position of its arms.

The walk-helper application also includes an automated trajectory correction system that uses the onboard 2D LIDAR sensor to scan the layout of the environment around the robot. This information is used to improve the safety and efficiency of the displacements in complex environments, allowing the robot to guide the user to the desired walkable area while avoiding accidental collisions.

5.2. Contributions to the state of the art

This work presents validation of the second generation of the Assistive Personal Robot (APR-02) as a walk-helping tool and the assessment of the automated trajectory correction system, designed to increase the efficiency of the displacements performed by the users while being aided by the robot. This validation has been performed by means of analyzing the obtained results when deploying the mobile robot in a real scenario with real users.

The first experiment provides qualitative assessment obtained directly from the users after using the APR-02 as a walking aid device. This experiment consisted on asking four different volunteers (aged 25, 41, 54 and 71 years old) to complete a set of common daily activities while using the mobile robot to perform the required displacements.

The second experiment provides a quantitative evaluation of the effectiveness of the automated trajectory correcting procedure presented in this work. This evaluation is achieved by comparing the performance of two users that must navigate across a 15 meters long corridor filled with a set of obstacles partially blocking the way. In this experiment, the first user will completely rely on itself to control the robot, while the second user will be assisted by the automated trajectory correction procedure.

Finally, this work provides relevant information on the acceptance and use of assistive robots in real scenarios, along with the benefits of embedding automated trajectory correction procedures to increase the level of automatization of the guiding system.

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Chapter 6

Development of a second-generation APR robot for autonomous monitoring of ambient conditions

6.1. Introduction

The pursue of new and innovative methods for gathering environmental data has rapidly become a subject of interest in the field of Ambient Intelligence, initially popularized by the concept of Smart Cities, and lately, the concept of "Internet of Things". The possibility of interconnecting large number of sensors to gather and distribute information in a large scale is changing the way we analyze our surroundings, looking for more efficient and less intrusive ways of improving energetic efficiency, safety and comfort of our buildings and cities.

The importance of maintaining appropriate ambient conditions in indoor areas is presented in [1], were the air quality, temperature and humidity of multiple schools in Aveiro, central Portugal is studied. Results showed that temperature and relative humidity in most of the schools was outside the recommended ranges, along with high concentration levels of CO_2. This demonstrates that important parameters that have a direct impact on safety, health and structural integrity such as illuminance and humidity are usually overlooked, potentially increasing the risk of domestic falls in older adults [2] and health issues related with the long-term exposure to inappropriate levels of relative humidity [3].

This chapter proposes the use of the second-generation APR robot to perform autonomous explorations inside a known area while monitoring temperature, humidity and illuminance several comfort-related parameters, providing a visual representation of the conditions found during the surveillance.

6.2. Contributions to the state of the art

In this work, the APR-02 robot is equipped with multiple sensors (temperature, illuminance and humidity) that, combined with the robot capability of locating itself inside a map, can provide a visual representation of the ambient conditions found during the exploration process.

Our research group has previous experience in this field, presenting multiple works aimed to analyze ambient conditions [4] and also to detect gas leakage sources [5,6], improving comfort and safety in indoor locations.

One of the main contributions to the state of the art of this work is the way the mobile robot records and displays the gathered data. In most common autonomous robots the map is interpreted as a matrix, thus meaning that large or irregular maps must sacrifice accuracy in behalf of efficiency and memory. In the case of the APR, the robot uses a two dimensional point cloud to represent its environment, meaning that the accuracy of the robot is not limited by the dimensions the matrix that contains the map, but by the exactitude of the sensor used to locate the robot inside the working area.

Another improvement over previously presented autonomous mobile robots is the way the robot identifies its position inside a map (Slef Localization And Mapping or SLAM for short). In this work the APR robot uses a variation of the SLAM technic known as Iterative Closest Point (or ICP for short) [7]. In this variation, the ICP is modified in order to combine the data provided by the encoders of the robot [8] to compute an initial estimation of the position of the robot, reducing the number of iterations required for the ICP to identify the rotation and translation that must be applied to the last LIDAR scan. Additionally, the implemented ICP variation will also retrieve the rotated points along with the rotation matrix, increasing the efficiency of the system.

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Chapter 7

Creation of automated temperature, illuminance and humidity reports using the APR-02 robot

7.1. Introduction

As shown in [1], the deployment of a Wireless Sensor Network (WSN) accessed through a web-based interface can be used to monitor ambient conditions, using this information to guide user's behavior with the objective of reducing power consumption. This technology is not limited to industries and households, as WSN have also been deployed in larger scenarios. An example of the use of distributed sensors networks is presented in [2], were multiple citizens act as independent nodes gathering environmental data related to multiple parameters such as the NO_2 concentrations in their cities. Another example is provided in [3], were a WSN is deployed in order to monitor traffic in the municipality of Shanghai.

This chapter is presented as the evolution of the work described in [4] and is focused on automatizing the analysis of the environment conditions monitored by the autonomous robot APR-02 during its explorations. The main objective of this generation of automated reports is not only to allow the robot to detect and evaluate inappropriate ambient conditions, simplifying the task of maintenance personnel, but also to be able s to communicate and adjust the behavior of the different actuators located around the working area in future projects.

For this experiment, the APR-02 robot is equipped with an embedded ARM-based sensor board containing temperature and humidity (SHT21 from Farnell [5]) and illuminance (TSL2561 from TAOS [6]) sensors used to monitor the ambient conditions found during the explorations. This board is connected to the onboard computer through one of the USB ports located at the base of the robot. The sensor is located over the left shoulder of the robot to maximize exposure to light, also ensuring that the temperature sensor is far from any component that may generate heat.

In order to classify the comfortability levels of the temperature, illuminance and humidity found during the explorations, the obtained values are compared with the standards defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE [7]). This information is finally used to create a mesh that visually identifies the areas of the map whose temperature, illuminance and humidity are not considered adequate.

7.2. Contributions to the state of the art

The deployment of mobile robots in outdoor environments is not a new concept, especially after the popularization of driverless cars and aerial unmanned vehicles (UAV) [8, 9, 10]. As an example, [11] shows the use of an UAV to monitor and detect health problems in a forest located in New Zealand.

Some of the main challenges faced when deploying autonomous mobile robots designed to work in indoor environments are the lack of space, absence of accurate positioning systems, and environments conceived to maximize the mobility of humans and not robots.

The autonomous navigation capabilities of the APR-02 allow precise maneuvering in complex indoor environments, thus meaning that the mobile robotic platform is able to navigate in real indoor environments. In the proposed work, the APR-02 robot performs explorations that includes navigating across doorways in order to reach all the required destinations.

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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. Design and implementation of the first generation Assistant Personal Robot (APR)

This section discusses the results of the paper presented in chapter 4 of this thesis "Assistant Personal Robot (APR): conception and application of a tele-operated assisted living robot".

The Assistant Personal Robot (APR) is conceived as a mobile platform designed to provide assistive and tele-operated services for older adults and people with mobility impairments. The control of the robot is performed through a remote Android application that provides real-time audio, video and motion-control over the APR robot.

The robot is driven by means of three omnidirectional wheels shifted 120 degrees (kiwi drive), allowing it to move in any direction and to rotate over itself. The high mobility capabilities provided by this holonomic motion system allows it to safely operate in complex indoor environments that including doorways and narrow spaces.

The main interface used to interact with the APR is the Android tablet located at the top of the robot. The use of an Android tablet is justified as it integrates and provides easy access to the multiple sensors and network capabilities required in order to provide a reliable telepresence system. The used device also has enough computational power to withstand the CPU load required to simultaneously offer a bidirectional videoconference system, reception of high-level motion orders, generation and transmission of low-level commands to the MCB (Motors Control Board), and wireless communication.

The motors that control the head pan/tilt, arms position and motion of the robot are directed by the Motors Control Board (MCB) located at the base of the robot, this board includes an ARM Cortex-M4 based Microcontroller with an STM32F407VGT6 processor from STMicroelectronics. The main objective of this board is provide a bridge between the high-level orders transmitted by the Android device and the multiple motors of the robot. Additionally, the microcontroller unit also analyzes the data provided by the onboard LIDAR device to perform collision avoidance procedures.

The reliability of the APR robot was tested in several case-scenarios including relative long range communications (a distance of 150 km between the robot and the operator) with positive results. The use of an external server along with the UDP Hole Punch technique performed by both the client and server application allowed the communication even through non-configured routers. The embedded safety procedures such as the detection of broken communications and the capability of the robot to override motion orders when obstacles are detected in front of it proved to be effective, stopping the robot immediately to prevent dangerous and uncontrolled situations.

Finally, the use of different threads implemented in the client and server applications successfully removed the propagation of errors between the different services provided by the robot. Future work will be focused on the development of some of the proposed applications presented in section 6 of the paper that are not yet implemented.

8.2. Development of a walk-helper functionality for the APR-02 robot to improve mobility in older adults and people with mobility impairments.

The results discussed in this section corresponds to the results presented in the paper “Extending the application of an Assistant Personal Robot as a walk-helper tool for people with reduced mobility” described in chapter 5.

The objective of the presented work was to improve the balance of older adults while performing displacement in domestic environments through the use of the APR-02 as a walk-helper device. To improve the efficiency of the displacements, an automated path correcting system was also presented.

The evaluation of the presented application was carried out by means of performing a set of two different experiments. The first experiment was aimed to obtain a qualitative opinion provided by the users after interacting with the APR-02 robot working as a walk-helper device. For this, a set of four volunteers (aged 25, 41, 54 and 71 years old) were invited to perform different tasks while using the developed robotic mobile platform for the displacements. The average time required for the users to get used to the controls of the robot was approximately five minutes. Results showed that all four volunteers considered that the robot increased their confidence during the displacements, this is especially relevant in the case of volunteer U1 due to her age. Results also showed that the height and size of the volunteers slightly conditioned their comfort when holding the hands of the robot. Finally, the answers provided by the users when asked if they would have the robot at home showed a general interest on introducing the APR robot in their household. The only participant who indicated that he would not have the robot at home justified his answer by stating that he did not have enough space for it.

The second experiment was aimed to evaluate the automated path correction system. This evaluation was carried out by one of the APR developers and the volunteer U4 from the previous experiment. For this experiment, the most trained user (the APR developer) had to manually control the robot across a corridor containing several boxes blocking the way, trying to perform the minimum number of trajectory corrections. The same experiment was then performed by volunteer U4, but now with the robot performing automated trajectory corrections. Results showed that the first user required up to 6 trajectory adjustments (a total of 27 state transitions) to reach the end of the experimentation area, while volunteer U4 only required a single correction (a total of 7 state transitions).

The obtained results proved that the walk-helper application embedded in the APR-02 improved the stability and balance of the users while performing displacements. Additionally, the automated trajectory correction system was able properly guide the user across the desired walkable areas, significantly reducing the number of times the user had to perform additional actions in order to reach the desired destination.

8.3. Development of a second-generation APR robot for autonomous monitoring of ambient conditions

This section discusses the results of the paper presented in chapter 6 of this thesis "Preliminary application of an Assistant Personal Robot as an ambient monitoring tool".

The methodology evaluated in this chapter is based on the results obtained through the deployment of the second generation autonomous mobile robot APR-02 in a real environment to provide a mobile, accurate monitoring system. The main objective of this work was to allow the robot to create an enhanced visual representation of three different comfort-related parameters (temperature, illuminance and humidity) evaluated while navigating across the second floor of the Polytechnic School from the University of Lleida. This work was aimed to facilitate the task of identifying potential problems caused by inappropriate ambient conditions.

To provide the autonomous navigation capabilities required for this project, the robot implements a "self localization and mapping" procedure based on a variation of the ICP (Iterative Closest Point) algorithm. The same algorithm is used to generate the map of the area used for navigation and for data representation. Finally, the robot uses the A* algorithm to generate the path between its initial position and the target destination.

During the presented experiment, the robot took a total of 394 samples along the approximately 41 meters traveled during the 218 seconds that lasted the exploration. This experiment was performed during the late hours of a cold winter day, with only half of the lights of the corridor switched on. The obtained results showed a temperature variation of almost one degree between the hottest spot (center of the corridor) and the coldest position (hall entrance with a large window). The gathered data also showed that there is a loss of heat near the emergency exit. These results indicate that the efficiency of the HVAC system could be increased by improving the insulating materials used at the emergency exit and the main hallway window. The illuminance report indicated a clear lack of illumination through the entire corridor. This was expected due to the lack of sunlight and also as half of the lights of the corridor were switched off during this exploration. Finally, the humidity report indicates that humidity raised when the mobile robot navigated near the hallway window and the emergency exit located at the end of the corridor, this was probably caused by the condensation of water at the window, and air filtrations through the emergency door sealing.

The obtained results showed that the autonomous version of the APR robot can be deployed as an ambient monitoring tool, successfully monitoring and mapping the temperature, illuminance and humidity levels of the explored area. Additionally, the graphic representation of the ambient conditions provides useful information aimed to identify and locate areas were corrective actions can be performed in order to improve energy efficiency. Future work will be focused on generating automated reports designed to automatize the control of different actuators in order to maintain adequate ambient conditions.

8.4. Creation of automated temperature, illuminance and humidity reports using the APR-02 robot.

This section discusses the results of the paper presented in chapter 7 of this thesis “Automatic supervision of temperature, humidity, and luminance with an Assistant Personal Robot”. The methodology evaluated in this chapter must be considered as the evolution of the methodology presented in the previous work

“Preliminary application of an Assistant Personal Robot as an ambient monitoring tool”.

For this experiment, the autonomous navigation system implemented in the APR-02 robot was largely improved, allowing it to operate in realistic environments, including navigating across doorways and narrow spaces. The main objective of this work was to design a procedure capable of navigating through real and complex environments, generate accurate maps displaying temperature, illuminance and humidity, and to automatically generate a report showing the areas of the map whose ambient conditions were located outside the recommended range.

To determine if the ambient conditions found during the exploration were appropriate, the gathered data was compared to the standards defined by the ASHRAE. This comparison allowed the classification and segmentation of the measured values in different ranges according to their level of adequateness. It is important to remark that the considered as “ideal” ambient conditions may vary depending on the season of the year and clime of the region.

For this experiment, the robot was requested to perform an exploration that consisted on: leaving the laboratory, reaching the emergency exit located at the end of the corridor, visiting the hall entrance, and finally returning to its charging area. The exploration lasted 760.8 seconds and the robot traveled a total distance of 98.08 meters at an average speed of 0.12 meters per second. The number of temperature, humidity and illuminance samples taken during this exploration was 1692. The results obtained during the exploration showed that the thermal conditions were appropriate for a hot summer day. Although not optimal, the relative humidity conditions found during the exploration were within acceptable levels. Finally, the illuminance report shows that the corridor was not properly lit, but the light conditions on the laboratory were appropriate.

Finally, it is important to note that although the temperature lectures obtained by the thermal sensor ranged between 26.2ºC and 25.3ºC, the heat produced by the microcontroller caused a temperature increase of around 1.12ºC, this offset was subtracted during the analysis process.

Chapter 9

Conclusions

This PhD Thesis addresses the improvement of the quality of life (QoL) in older adults and people with reduced mobility through the development and validation of two different versions of the Assistant Personal Robot.

The major achievements of this PhD are the following:

- **Development of the remote control system for teleoperated services with the first Android-based version of the APR robot.**
  The development of the Android client and server applications used to control the first version of the APR were particularly challenging. The lack of existing Android API for performing real-time bidirectional video and audio transmission, the large number of sensors that had to be accessed simultaneously, the internet peer to peer communications through NAT and non-configured routers, and automatically adjusting the configuration of the videoconference system according to network performance were only some of the main obstacles faced during this development stage. The paper presented in chapter 4 provides an in-depth description on the methods used to overcome such challenges. Long-term results have proven the reliability of the developed mobile robot through its constant use in several demonstrations performed during the last 3 years.

- **Improving mobility through the use of the APR-02 as a walk-helper assistant.**

  Maintaining an active lifestyle in older adults is one of the most decisive factors that will define their quality of life. The developed application embedded in the APR-02 robot was aimed to improve the users mobility by providing a stable structure to which they were able to hold on to, helping to maintain their stability and confidence during the displacements.

  The results obtained during the evaluation phase confirmed that the developed feature for the APR robot was able to improve the mobility capabilities of all the users during the displacements performed in a real environment. This was particularly perceptible with the volunteer U1, a 71 years old female. Additionally, the automated trajectory correction system developed for the walk-helper application was able to reduce the number of corrective maneuvers that the users needed to perform in order to navigate across the experimentation area.

- **Automated monitoring of ambient conditions in real scenarios.**

  This work proposed the development of an ambient monitoring tool embedded in the second generation of Assistant Personal Robot. The implemented autonomous navigation system based on a variation of the Iterative Closest Point algorithm allowed the robot to navigate across real environments that included complex layouts such as narrow spaces and doorways.

  The robot was successfully deployed in the second floor of the Polytechnic School from the University of Lleida. During the experiments, the robot monitored the temperature, illuminance and humidity levels, providing accurate location for each one of the gathered samples. The visual representation of the monitored parameters generated by the robot after each exploration showed a large variation between the measurements obtained in different locations of the same area, highlighting the benefits of using mobile sensors when compared to other options such as WSN-based solutions. Finally, the mobile robot was able to identify and locate the areas of the map whose ambient conditions were not contained inside the ranges recommended by the ASHRAE.

Chapter 10

Future work

This section presents and describes several research branches opened by the results of this thesis that can be addressed in the future. The main goal of this thesis has been the improvement of the quality of life of elderly people and people with mobility impairments through the incorporation of an Assistant Personal Robot. Future work will be aimed to develop new AAL-oriented applications by taking advantage of the autonomous capabilities provided by the second version of the APR robot. One interesting proposal is to combine the autonomous navigation capabilities with the use of the multiple onboard RGB-D cameras in order to develop a surveillance application that would be capable of detecting if a person is laying on the floor.

Although the APR was initially conceived only as an assistive robot for improving the quality of life of older adults and people with mobility impairments, the autonomous capabilities of the robot along with its compatibility with a large number of sensors (any device that can be connected to an USB port) is expanding the initial scope of the project. The first steps towards the use of the APR-02 robot as a scientific mobile platform were already taken and presented during the development of this thesis in chapters 6 and 7. In this direction, one of the applications that are currently under development is the use of the APR robot to identify and locate potentially harmful gas leakage sources.

Nomenclature

A*	A-star algorithm
AAL	Ambient Assisted Living
ABS	Acrylonitrile butadiene styrene
AC	Alternating Current
ADK	Android Accessory Development Kit
AmI	Ambient Intelligence
API	Application Programming Interface
APP	Application
APR	Assistant Personal Robot
ARM	Advanced RISC Machine
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CPU	Central Processing Unit
DC	Direct Current
DoF	Degrees of Freedom
HVAC	Heating Ventilation and Air Conditioning
ICP	Iterative Closest Point
IoT	Internet of Things
IP	Internet Protocol (address)
IR	Infrared
IT	Information Technologies
JPEG	Joint Photographic Express Group (compression algorithm)
LAN	Local Area Network

LIDAR	Light Detection and Ranging
MCB	Motors Control Board
MCU	Microcontroller Unit
NAT	Network Address Translation
OTG	On The Go
P2P	Peer to Peer
PID	Photo-Ionization Detector
PWM	Pulse-Width Modulation
QoL	Quality of Life
RF	Radio Frequency
RFID	Radio Frequency Identification
RGB-D	Red Green Blue Depth
SLAM	Simultaneous Localization and Mapping
TCP	Transmission Control Protocol
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
USB	Universal Serial Bus
WAN	Wide Area Network
WSN	Wireless Sensor Network