Universitat de Lleida

Application of autonomous mobile platforms for environmental supervision and gas leakage localization

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TESI DOCTORAL

Application of autonomous mobile platforms for environmental supervision and gas leakage localization

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CERTIFICA:

Que la memòria “Application of autonomous mobile platforms for environmental supervision and gas leakage localization” presentada per Daniel Martinez Lacasa per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

Lleida, 17 de novembre de 2016

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Resum

En aquesta memòria es presenta la recerca realitzada en l'anàlisi de condicions ambientals en zones de freqüent ús humà mitjançant la utilització de robots mòbils equipats amb sensors de gasos que també aporten la capacitat de detectar substancies volàtils tòxiques.

L'ús de la robòtica per aplicacions d'intel·ligència ambiental denominat "Ambient Intelligence" (AmI) es troba cada cop més extens tant com a nivell comercial com en recerca científica. L'augment de popularitat d'aquest tipus d'aplicacions promouen l'aparició de noves metodologies que permeten millorar les condicions de vida de les persones en entorns habitables o de treball.

Aquesta memòria presenta un conjunt de treballs de recerca científica sobre una línia d'aplicació en AmI basat en el desenvolupament i control de robots mòbils per realitzar diferents tasques de supervisió de l'entorn de forma autònoma. En primer lloc, la memòria presenta una proposta de sistema de control per un "Assistant Personal Robot" (APR) basat en una arquitectura multi-agent que permet l'execució de diferents processos del robot paral·lelament i de forma efectiva. El següent treball descriu una aplicació AmI de control de condicions ambientals basada en el desenvolupament d'un robot mòbil capaç d'explorar l'entorn i analitzar la informació ambiental per tal de detectar possibles alteracions. En tercer lloc, es presenta la caracterització d'un túnel de vent en el qual s'alliberen substancies tòxiques volàtils a molt baixa concentració per tal que siguin detectades per un robot mòbil en diferents condicions experimentals tenint com a objectiu final la localització de les fonts. Per últim, s'estudia la creació d'un agent que permetrà que un robot mòbil realitzi diversos experiments de camp en els quals ha de desplaçar-se per entorns reals tot mesurant dades de concentració de gasos i vent a l'ambient. Aquest agent ha permès estudiar la viabilitat dels diversos mètodes proposats per a la localització de les fonts de gas analitzades. Els resultats i conclusions obtinguts en aquesta memòria demostren l'efectivitat d'aquestes metodologies com a via per al desenvolupament de noves aplicacions AmI.

Resumen

En esta memoria se presenta la investigación realizada en el análisis de condiciones ambientales en zonas de frecuente uso humano mediante la utilización de robots móviles equipados con sensores de gas que también aportan la capacidad de detectar sustancias toxicas volátiles.

El uso de la robótica para aplicaciones de inteligencia ambiental denominado “Ambient Intelligence” (AmI) se encuentra cada vez más extenso tanto como a nivel comercial como en investigación científica. El aumento de popularidad de este tipo de aplicaciones promueve la aparición de nuevas metodologías que permiten mejorar las condiciones de vida de las personas en entornos habitables o de trabajo.

Esta memoria presenta un conjunto de trabajos de investigación científica sobre una línea de aplicación en AmI basado en el desarrollo y control de robots móviles para realizar diferentes tareas de supervisión del entorno de forma autónoma. En primer lugar, la memoria presenta una propuesta de sistema de control para un “Assistant Personal Robot” (APR) basado en una arquitectura multiagente que permite la ejecución de diferentes procesos del robot paralelamente y de forma efectiva. El siguiente trabajo describe una aplicación AmI de control de condiciones ambientales basado en el desarrollo de un robot móvil capaz de explorar su entorno y analizar la información ambiental para detectar posibles alteraciones. En tercer lugar, se presenta la caracterización de un túnel de viento en el cual se liberan sustancias toxicas volátiles a muy bajas concentraciones para que sean detectadas por un robot móvil en diferentes condiciones experimentales teniendo como objetivo final la localización de las fuentes. Por último, se estudia la creación de un agente que permitirá que un robot realice diferentes experimentos de campo en los cuales ha de desplazarse por entornos reales midiendo datos de concentración y viento al ambiente. Este agente ha permitido estudiar la viabilidad de los diferentes métodos propuestos para la localización de las fuentes de gas analizadas. Las conclusiones obtenidas en esta memoria demuestran la efectividad de estas metodologías como vía para el desarrollo de nuevas aplicaciones AmI.

Summary

In this thesis is introduced the research performed on the analysis of the ambient conditions in human frequented places by means of using mobile robots equipped with gas sensors that also provide the capability of detecting toxic volatile substances.

The use of robotics for Ambient Intelligence (AmI) applications is getting extensive in a commercial level as well as in scientific research. The increase of popularity of such applications fosters the appearance of new methodologies that allow the improvement of people living conditions in households or work environments.

This memory presents a set of scientific research works following an AmI application line based on the development and the control of mobile robots in order to perform different autonomous tasks on environmental supervision. First, the memory presents a control system proposal for an "Assistant Personal Robot" (APR) based on a multi-agent architecture that allows the execution of different robot processes simultaneously in an effective way. The next work describes an AmI application of ambient control based on the development of a mobile robot capable of exploring its environment and analyzing the ambient information in order to detect possible anomalies. In third place is presented the characterization of a wind tunnel in which some toxic substances are released at very low concentrations in order to get detected by a mobile robot under different experimental conditions having as the main objective the localization of the sources. Finally, it is proposed the creation of an agent that enables a mobile robot to perform several field experiments in which the robot has to move through real environments while measuring information about gas concentration and wind conditions on the ambience. This agent has allowed the viability study of the different proposed methodologies for the gas source localization. Results and conclusions obtained in this memory demonstrate the effectiveness of such methodologies as a way to develop new AmI applications.

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Chapter 1

Introduction

The increasing tendency on the globalization of the information technologies experimented from the last decades has motivated the use of a wide scope of different technologies for being used in an interconnected paradigm in order to improve the quality and the accessibility of information. From such technologies, robotics is considered one of the most important science to develop new applications which can produce an important improvement on the quality of life of worldwide people. Robotics for industrial applications are actually well-known; but during last years, several companies have developed different products based on robotics for domestic environments such as cleaner robots [1], cooking robots [2], assistant robots [3,4], and smart home installations [5]. In scientific research, robotics has application to many different research fields in order to provide improved and automatized methodologies [6]. Moreover, current research papers published in journals on robotics are actually focused on providing high independence levels, advanced robot routines, complex artificial intelligence procedures, adaptability to environment, computer vision algorithms, collaborative behaviors with other robots and humans, and more.

The last advances on information technologies have fostered the emergence of new concepts with the main objective of bringing such technologies closer to the daily life of people. Ambient Intelligence (AmI), Ambient Assisted Living (AAL), Smart Cities, and the Internet of Things (IoT) are some of those concepts which are reaching high popularity among the most important technological companies [7,8,9] as well as among the scientific community by means of new dedicated journals and conferences.

This thesis addresses the use of robotic technology for the development of new applications in the scope of the previously described concepts. The aim is to develop and validate new methodologies for the detection of inadequate or harmful environmental conditions in indoor areas as well as locating the source of the problem by using a mobile robot.

1.1. Ambient Intelligence

Since the last decade the society, especially in developed countries, has experimented an important increase on the presence of information technologies in personal daily life by the emergence of new internet technologies, smartphones, wearable devices, social networks, and so on. The Ambient Intelligence (AmI) paradigm was born from this tendency in order to integrate the power of the information technologies to human-living environments instead to a single physical device. As explained in [10], such digital environments must be sensitive, adaptive, and responsive to human behaviors by means of using embedded, non-intrusive, and secure devices. The objective of those implementations is to provide the “intelligence” of computation at human environments in order to automatize some human daily routines and decisions as well as keeping a healthy atmosphere by information gathering and processing. This concept allows the development of an extensive scope of new applications with the possibility of including different multi-disciplinary methodologies on, for example: artificial intelligence, signal processing, communications, energy, health, etc.

1.1.1. Research and applications

In scientific research, the number of publications in this field is continuously increasing as well as its popularity in the global community. As an example, [11] presented a system-level programing language which is used to develop free AmI applications with internet-enabled sensor and actuator networks. The scenario of this work is a warehouse with a distributed monitoring and control system.

Adding advanced artificial intelligence processes to an AmI system is considered in [12] where a reasoning framework was applied to an AmI-enabled institute. A well-defined context model is essential in order to provide effectiveness to the results of the reasoning system. In a similar way, the ClassMATE framework [13] offers an AmI architecture for educational environments with context-awareness, device management (interactive boards, smart desks, etc.), and adaptive behaviors on student profiles. In [14], the use of AmI systems is proposed to assist athletes with different profiles in their trainings and tasks in order to maximize its effectiveness. This method uses hardware devices to gather real-time information about the user (health, localization, and progress), the environment, the weather, etc. Then, a decision engine computes the best actions to follow according to the analyzed variable factors.

Health care environments such as hospitals are also considered for integrating AmI systems. In [15] the use of AmI devices is proposed to improve the performance of clinical facilities by means of increasing patient accessibility plus automatizing doctor and nurse routines where an experimental setup was carried out in a patient room for method validation with users of different ages resulting in a successful feedback report. As an example of a health care AmI system, fig. 1.1 shows a communication layer architecture based on body sensors and high-level services. The application of new control technologies in a health care context can involve a clash with some ethical and legal constraints due to the storage of sensitive information and the appearance of security breaches in systems with processes and parameters that can directly affect the patient health. The work published in [16] addresses a discussion on some case studies in which AmI systems oriented for health care can be compromised in terms of ethics and legality.

Power consumption is usually one of the most significant expenses in any company or household environment, for that reason, the application of AmI systems on energy optimization is also addressed to save energy and other related costs. In [17] a control system for smart LED lightning is proposed for commercial areas, offices, or residential areas. This system is based on a wireless sensor network that obtains luminance intensities, human activity, and other parameters as feedback to adjust LEDs brightness for each zone. According to this analysis, this method saves up to 10% of energy without compromising the lightning conditions.

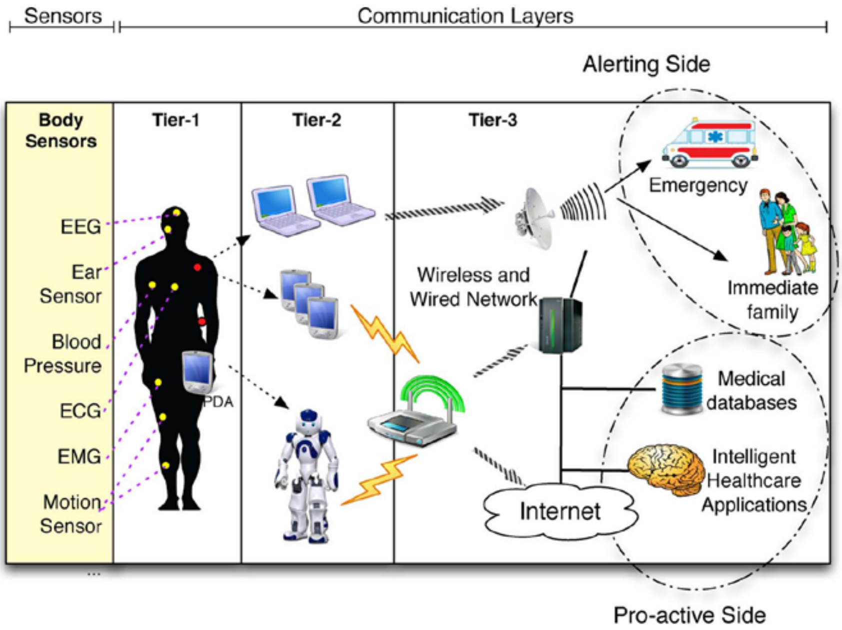

Fig. 1.1. The architecture of a Body Area Network (BAN) for a health care AmI system [10]. © [2013] IEEE

For industrial environments, the work presented in [18] proposes the application of an AmI platform designed for gathering energy-related information for being process by context-aware services in order to improve the energy efficiency optimization of an industrial facility. On the same line, an AmI decision system was proposed in [19] to be implemented for manufacturing process optimization as well as for energy efficiency. Such method uses sensor networks and software ontology to enhance the product/process design system which allows the engineers to implement more energy efficient systems and ecologically optimal.

Sensor technologies are usually the main part of an AmI system, for that reason it is important to develop new sensor algorithms to increase environment adaptability and context-aware accuracy. The work presented in [20] presents an AmI scenario where an accurate identification of users is required in order to satisfy personalized needs. To fulfil with this requirement, it is proposed the use of a 3D face recognition algorithm applied to stereoscopic images and capable of identifying the user and his emotional status. Furthermore, the use of service robots as a mobile platform for sensors and actuators is also studied for an AmI environment. In [21] the integration of a service robot to a smart home is proposed and implemented by means of a Universal Plug and Play protocol (UPnP). The conclusions highlights the feasibility of their method as well as the possibilities of developing new interesting services.

1.1.2. Related concepts: Ambient Assisted Living

The term Ambient Assisted Living (AAL) englobes all Ambient Intelligence applications in which control technologies, sensors, and other devices are used in order to ease and improve the daily life of common people generally in household domains giving special emphasis on increasing the independency levels of aged persons and people with disabilities. In this concept, there are many different kind of applications as well as many different devices like fixed and/or distributed systems, wearables, and mobile robots which are engaged to perform different embedded healthcare tasks inside human environments with different levels of automation. The objectives, possibilities, and challenges of AAL systems are analyzed and discussed in [22] concluding on a positive view of these safety environments but also considering the risk of social isolation. Specifically, [23] published an extensive and accurate review of the state-of-art in AAL frameworks, architectures, technologies and standards with an overview of real deployments of AAL systems whereas [24] proposes other AAL applied technologies based on computer vision.

The integration of a health monitor system was proposed in [25] focusing on scenarios where an elder is living alone and needs assistance without losing independency. The methodology consists on detecting domestic problems and accidents by means of using non-intrusive devices. For example, [26] proposed the use of a wearable device composed by an accelerometer and a logical unit for fall detection engaged with a wireless communication for alarm notification. On the same direction, [27] presented a flexible thermoelectric generator to be used as a battery for wearable biometric sensors which can produce up to 32nW at an ambient temperature of 40ºC.

Some specific domestic tasks are also considered for implementing AAL technologies such as kitchen-related tasks [28] in which the autonomy of elder and disabled people is increased through context-awareness and artificial intelligence without high adaptation efforts.

Robotics has much potential when used for AAL environments and its presence are growing in scientific research [29]. In [30] has been developed a nursing-care assistant robot (fig. 1.2) specially designed for lifting up and transfer patients between the bed and the wheelchair autonomously. Moreover, this kind of autonomous assistive robots requires a decision-making procedure and, in some cases, they have to be collaborative with other robots to operate in the same environment like the case presented in [31]. This scenario implemented a task planner for a multi-robot system that manages the behavior of the different devices depending on its requirements of causal, temporal, resource and information dependencies.

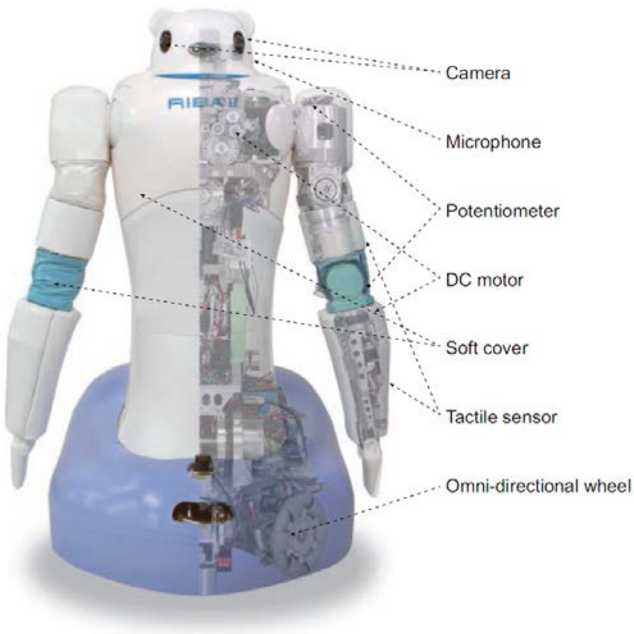

Fig. 1.2. A nursing robot capable of lifting up humans proposed by [30]. © [2013] IEEE

1.1.3. Related concepts: Smart city

The context of a smart city can be informally described as a conventional AmI environment expanded to a large heterogeneous dimension with so much more variables to deal with. It is easy to find examples of inconsistent uses of the term “smart city” referring it as a fuzzy concept. In a scientific and technological perspective [32], the concept of smart city involve the use of information technologies like computation, sensors, communications, and artificial intelligence to autonomously define new city policies, strategies and programs in order to achieve a sustainable development as well as a better quality of life for its citizens.

The methodologies applied for engaging smart cities are mainly based on the self-control and self-optimization of different urban management processes. As an example, [33] presented several technologies and applications for smart cities focused on smart sensing systems, for instance, a smart water distribution system (Fig 1.3), smart grids for electricity distribution systems, adaptive traffic systems, etc. Smart lighting is also addressed for smart cities like in [34] in which is proposed a control and a connectivity systems that can significantly reduce the global energy consumption of urban territories.

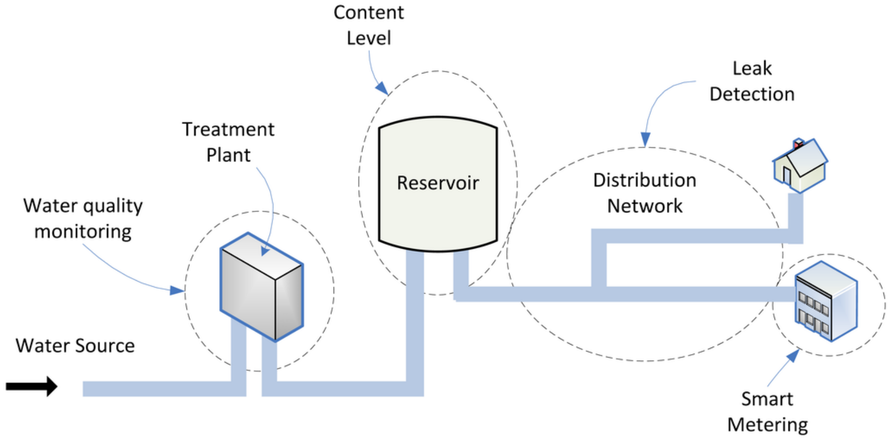

Fig. 1.3. Concept of a sensing water distribution system for smart cities [33].

The validation step of a research based on applying new smart city methodologies can conclude with inaccurate results due to a non-realistic reduced experimentation environment. For example, [35] proposed the creation of “living labs” for method validation in order to motivate city leaders to implement new smart city applications. The concept of “living labs” means the use of urban territories as a real-world testing area. The work discusses the conditions and technologies to create “living labs” for smart cities. In a similar direction, [36] described some proved good practices proposed to develop smart cities and empirically analyzes the results of the implementations on Seoul and San Francisco.

The integration of new procedures on cloud computing, big data, and Internet of Things (IoT) [37] is actually being studied and developed to be used in a smart city context maximizing even more the efficiency and the effectiveness of smart city implementations and opening also, the way to develop new smart city applications.

1.1.4. Related concepts: Internet of Things

The emergence of smart cities and AmI systems fosters the integration of many different devices oriented to different contexts which usually are capable of engage external communications. The number of interconnected devices is currently growing in an important rate and is expected to exceed the 20 billion devices in 2020 according to different market predictions [38]. The Internet of Things (IoT) paradigm pretends to add a new conceptual layer on such devices (smartphones, sensors, actuators, AmI devices, etc.) to achieve and absolute interconnected scenario. According to [39], the IoT concept involve the characterization of an internet oriented (arcs – communication layer), things oriented (nodes – devices), and semantic oriented (sets – knowledge fields) environment.

A cloud-based architecture for IoT is presented in [40] through the implementation of a framework capable of discriminating sectors that require different needs of privacy, computation, storage and visualization without losing collaborating capabilities among them. During the last years some applications were designed to be used in an IoT environment such as the work proposed in [41] that describes the development of an AAL system for diabetes therapy by using the IoT concept in its implementations. As an example, [42] proposed the use of RFID and IoT technologies to provide access to real-time information about the life cycle of an enterprise product as well as be used as an anti-counterfeiting system and in [43] the dynamics and concepts of social networks are exported to the IoT, then called Social Internet of Things (SIoT) to provide effective object discovering services for scalar object networks.

1.2. Mobile robot agents

Robotics was born from the necessity of humans to automatize processes and to avoid their exposition on potentially dangerous situations by using the last technological advances on mechanics, electronics, physics, signal processing, and computer science. So, the main objective of a robotic platform is to perform autonomous actions or services which can be applied in a large number of different contexts providing precision, efficiency, and security. Robotics covers an extensive scope of applications that require different levels of complexity and adaptability, for instance, a robotic arm from a manufacturing facility, or an intelligent assistant robot.

A mobile robot agent is considered as a discretization of the robotics concept into intelligent agents. According to [44], agents are artificial intelligence entities provided with autonomy, reactivity, collaboration, and initiative behaviors that cooperate among them to conform a global intelligent system. So, this theory was assimilated by robotics in order to stablish a new theoretical basement for robot development. The term robot agent can be used in two different perspectives: 1) to define a unit from a set of heterogeneous robots that cooperate in order to accomplish the objective of such system; 2) to define a node process of a robot control system that performs an specific functionality and requires the cooperation of other node processes to achieve mobile robot full operability.

1.2.1. Hardware platforms

Currently there are a large number of commercial, non-commercial, military, emergency, research, and custom-made robotic platforms developed to perform something or to be capable of engaging different procedures. As an example of an agent-oriented robot, [45] presented a personal mobile robot that pretends to engage a symbiotic interaction with humans to overcome the robot limitations on perception, cognition, and execution. In [46] a robot agent was proposed as a bartender capable of dealing with multiple customers in a dynamic social environment. The exploration of pipeline installations is implemented in [47] by means of using a mobile robot agent with an agent-based control architecture. The development of multi-robot systems or swarm robot systems has been addressed during the last decade adding more complexity to its implementations due to collaborative behaviors, communication protocols, and heterogeneous systems [48].

In this thesis, custom-made robots are used as research platforms for mobility measurement and multi-agent control system development. First, the mobile robot “rBot” (fig. 1.4a) was developed to be mainly used as a mobile measurement platform for experimental validations. This two-wheeled platform can reach a maximum forwarding speed of 0.6m/s and is prepared to attach and receive information from any required sensor. Nevertheless, the robot has a stereoscopic camera and a laser range sensor fixed in its structure. The other mobile robot used in this thesis is the APR-02 (fig. 1.4b) which was designed as an assistant robot for AAL applications. This second platform has a powerful computational unit, a high mobility system based on three omnidirectional wheels, and a complete set of sensors. In this thesis, the APR-02 is used to develop a multi-agent control system capable of engaging an effective operability among the different robot required processes.

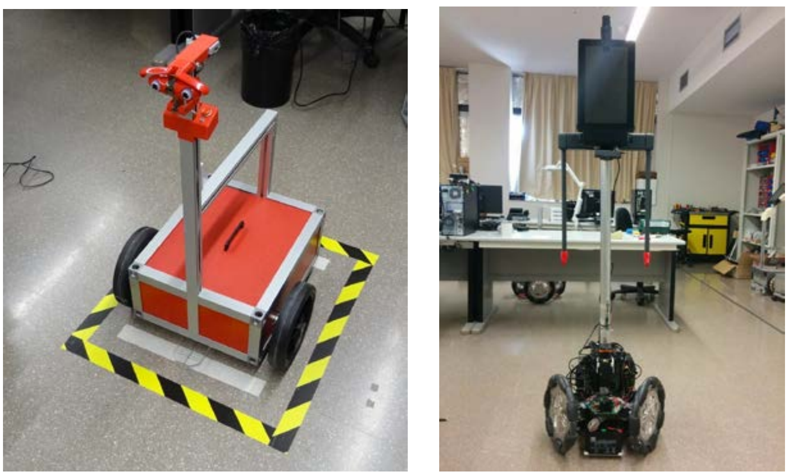

Fig. 1.4. (a) The mobile robot “rBot”. (b) The APR-02 under development.

1.2.2. Control system

Any robotic platform requires the implementation of a control system in order to provide an effective control and management of its functionalities allowing the robot to fulfill with the objective which has been made for. Control theory of signal processing field provides a solid basement to design feedback control systems in robot devices that can be exported to be used in many robot control procedures. However, newer intelligent robots also take advantage of methodologies from computer science and telecommunications which have expanded the ways to design complex control system architectures. Such advances on control system architectures have allowed the implementation of heterogeneous control processes executing simultaneously in the same robot unit with a constant cooperation among them. These control processes, called robot agents in this thesis, are designed as modular control units to engage a specific robot function, for example, a decision making process, navigation, localization, computer vision, sensor management, actuator management, etc.

Several architectures for robot control systems were proposed in the literature such as in [49] where the effectiveness of a multi-layer distributed control system is tested in a real mobile robot. On the same line, [50] describes a multi-agent architecture combined with a fuzzy logic control unit implemented to combine different controller responses. Alternatively, an entire control system architecture can be designed and applied to perform a specific function which requires high complexity levels. For instance, [51] presented a control architecture for quadruped locomotion capable of adapting its steps while displacing on irregular terrains. In [52], a complex speech interaction system is proposed based on the use of a distributed control architecture in order to synchronize different speech behaviors and achieve an effective and natural dialogue.

1.2.3. Simultaneous Localization and Mapping

The problem of robot localization was actively addressed during the last two decades by different proposals based on probabilistic approaches that compute relative robot poses from environment observation. The Simultaneous

Localization and Mapping (SLAM) problem was firstly discussed in late 80s [53,54] in order to find new methods to improve the autonomy of mobile robots. The main goal of such methods was to implement a spatial model of the physical features of the robot environment at the same time the robot is continuously localized in this model. This solution would provide important knowledge for the navigation procedures which would allow the robot to perform complex path planning methodologies.

The first SLAM proposals were published in the 90s opening two different ways to address the problem: the landmark-based association, and the volumetric association. On the one hand, the landmark-based SLAM techniques consist on the identification of environmental significant features called landmarks in which the robot tries to detect them in each iteration, and then, estimates the robot displacement. Usually, in this estimations are applied information filters due to the added uncertainty from errors on the landmark detection and from sensor noise. The map created by this method only has to store the information of the landmarks. First landmark approaches used Kalman filters for the association step with Gaussian distributions and linear motion models. However, in real cases non-linear functions are more suitable for robot motion model estimation, so, the Extended Kalman Filter SLAM (EKF-SLAM) was proposed in order to deal with this issue [55]. At this point it was achieved the first consistent solution for landmark-based SLAM and many different variations and improvements were proposed along the 2000s such as the optimized FastSLAM [56], the Unscented SLAM [57], and the camera-based visual SLAM [58]. On the other hand, the volumetric association alternative for SLAM uses the physics of the whole environment for robot pose estimation instead of some landmarks. This technique consists on processing two consecutive acquired sensor datasets (2D laser scans, 3D point clouds, etc…) to estimate its spatial transformation by applying a matching algorithm. The main motivation for new volumetric association approaches is the use of new high precision sensors for error minimization when aligning large datasets. The spatial representation are usually gridmaps in which is stored a discretized version of the robot environment composed by free or occupied cells. First approaches on volumetric association were published in the

90s in which is used iterative matching methods such as the Iterative Closest Point algorithm (ICP) [59] and other least-squares based solutions [60]. During the 2000s, the ICP algorithm was also popularly applied for scan-matching SLAM and new variations were proposed such as the Point-to-Line ICP (PLICP) presented in [61]. In addition, other scan-matching approaches focused on laser range sensors were also proposed [62]. However, the popularity of ICP-based methods fosters the development of new improvements as the one presented in [63] which provides more robustness and applicability dealing also with 3D mapping. The creation of 3D maps composed by point clouds or voxels is strongly addressed along the last ten years especially due to the commercialization of low-cost RGB-D cameras such as the Microsoft Kinect. The works presented in [64,65] describe a consistent 6 Degrees of Freedom (DoF) SLAM for 3D point cloud matching based on ICP algorithms. Moreover, the SLAM problem has been applied on multi-robot systems [66] opening a scope of new challenges such as map merging [67] and multi-robot exploration [68].

1.2.4 Navigation system

The adjective “mobile” in the term mobile robot implies that the robotic platform can modify its state in the spatial dimension by itself. This capability is provided by a locomotive mechanism that engages the robot to perform terrestrial, aerial, aquatic, or space displacements. Such propulsion mechanisms are managed by a control system which processes and converts high-level motion orders to compatible low-level signals. The navigation system is the control unit that emits such motion orders following an informed or a reactive path planning procedure in order to reach a specific spatial destination point or to perform an exploration pattern. These observation-based procedures gather and processes information from onboard sensors such as ultrasonic, vision, laser range, or global positioning system (GPS) which are the most used devices for robot navigation according to the literature. In addition, navigation systems are usually also aware of possible unexpected danger such as collisions with other static (stopped) or dynamic (moving) objects. In such cases, a mobile robot can simply be stopped until the danger disappears or the robot can perform a reactive correction of its path as an evasive maneuver [69].

In [70] a large-scale navigation system is presented based on the use of geodata provided from an open map repository and applies the A* algorithm for path planning. GPS coordinates and a laser range information are used for robot localization and path following. For complex-shaped environments, [71] proposed the creation of Voronoi Diagrams from maps for further path extraction by using the Fast Marching Method. As an alternative, genetic algorithms are used for path computing in a grid-based map representation, and next, the B-spline technique is used for path smoothing [72]. Newer mapping approaches based on point clouds provided from depth cameras or 3D laser sensors are used to create 3D maps (fig. 1.5) which are also considered for robot path planning in [73].

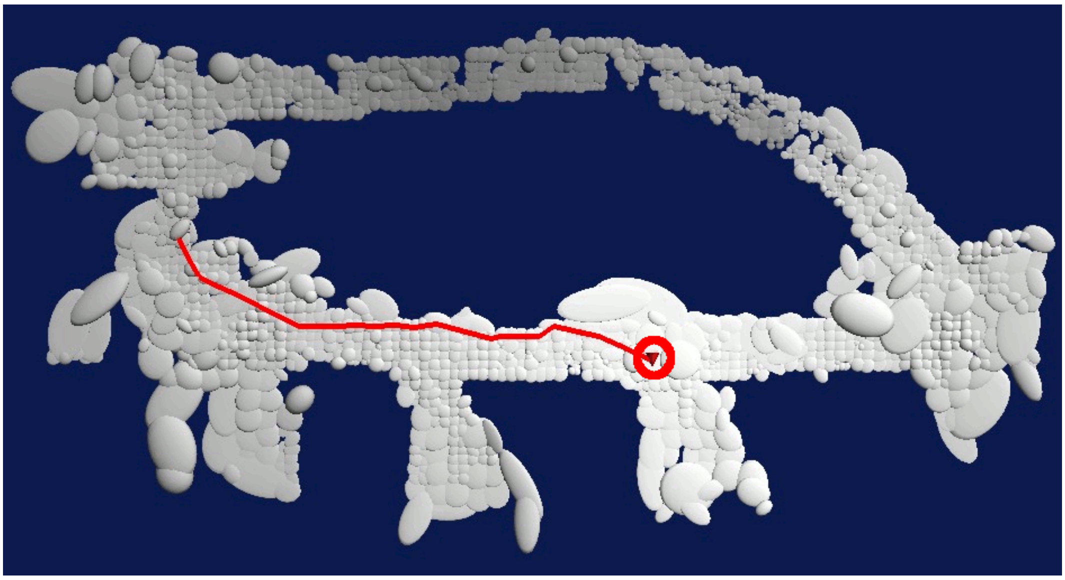

Fig. 1.5. An example of a robot navigable 3D map created from point-cloud processing [73].
© [2010] IEEE

The behaviors of mobile robots when integrating to human environments are carefully addressed in the literature with the main objective of deploying a human-friendly presence and providing security when developing its tasks [74]. In a more practical view, [75] described and validated a human-friendly navigation framework aware of human uncertainty areas while moving. In a similar way, the work presented in [76] proposes the use of a distributed camera system to human path pattern extraction for further use on robot path planning procedures.

1.3. Gas source localization problem

Maintaining a human safety environment is one of the different possible applications offered by AmI systems. However, in this field there are problems to face on that require a deeper study due to their high complexity such as the gas source localization problem. Currently, industrial facilities, institutional buildings, and other big indoor areas have distributed gas sensor networks that simple alerts whether any harmful gas is detected, and some of them, also shows where is the triggered sensor. Gas agents experiment a chaotic diffusion when released that can be also conditioned by the area shaping, wind behavior, gas flow rate, and many other factors. This problem has assented an own research line during the last two decades providing extensive analyses and practical solutions for different environments and by using different methodologies. The most popular solution is the use of mobile sensor platforms (mobile robot) combined with a navigation system guided by heuristics processed from sensor data. One of the main advantages of this solution is that the deployment of a previous infrastructure is not required for its use, so, there is a cost saving which is proportional to the area size of the supervised zone. Moreover, this methodology also provides high reliability sampling due to the capability of modifying the measurement spatial point in an almost infinite scale.

1.3.1. Research and applications

The gas source localization problem was firstly addressed by the scientific literature on the 90s [77] proposing several approaches on plume tracing and gas distribution modeling by means of using a mobile measurement platform. Mobile robots used for such applications are usually equipped with chemical sensors, anemometers, and sensors capable of detecting the shape of the navigable area. In such configurations the literature does not considers any other ambient information as relevant for its use on gas source localization algorithms. However, an alternative methodology from chemical sensors for detecting gas leakages was proposed in [78] in which a robot uses a remote-methane-laser-detector (RMLD) based on IR-optical spectral remote sensing technology.

In [79] is presented a comparison between two robot gas-tracking algorithms in terms of exploration time and traveled distance. Both approaches are reactive and develop different exploration patterns under the same experimental conditions in a controlled environment. Similar exploration patterns were implemented in [80] in which is proposed the use of a biologically-inspired algorithm for a multi-robot system.

Many research papers in this field try to obtain extensive background knowledge of this problem by the characterization of the environment and by the creation of gas distribution maps. In [81] is proposed a methodology to create gas distribution maps of volatile substances by using a mobile robot with a chemical sensor. Trying to locate the gas source by applying inverse methods from gas dispersion models is addressed in [82]. This approach generates different distribution models with a random search algorithm which are further assessed by several proposed cost functions.

Nevertheless, gas sensor networks are still considered for research as a viable solution of this problem such as in the work presented in [83] which proposes a distributed methodology on combustible leakage detection. In addition, in [84] is presented a similar approach but focusing on low power solutions.

1.3.2. SMART-IMS project

Part of this thesis have been developed within the scope of the SMART-IMS project titled “Signal Processing for Ion Mobility Spectrometry: Analysis of Biomedical Fluids and Toxic Chemical Detection” and granted by the Spanish Ministry of Science and Innovation (reference: TEC2011-26143). Ion Mobility Spectrometry (IMS) has been used in the past mainly for explosive and narcotics detection by security personnel. IMS offers minimal size, very good detection limits, simple or absent sample preparation, and analysis times faster than 1s. This project aims to apply advanced multivariate statistical signal processing techniques for the treatment of time-series of IMS spectra. Two experimental scenarios were considered in this project: The analysis of biomedical fluids by using a synthetic breath simulator; and the detection and localization of toxic leakages in uncontrolled environments by using a mobile robot. This last scenario is focused on detecting trace concentrations of toxic chemicals in uncontrolled environments where a variety of pollutants may be detected by the IMS sensor.

1.3.3. SIGVOL project

The second project supported by this thesis is titled “Signal enhancement for chemical instrumentation: applications in volatile metabolomics and mobile robotics olfaction” (SIGVOL). This project was granted by the Spanish Ministry of Science and Innovation (reference: TEC2014-59229-R) have been conceived from the results and conclusions of the previous research performed on the SMART-IMS project. The main goal is to develop new signal processing techniques to improve the performance of chemical instruments for metabolomics and chemical sensing for robotics. In a first scenario, it is proposed the development of a signal processing methodology to enhance the performance of a Multi-capillary Column / Ion Mobility Spectrometry (MCC-IMS) instrument in terms of selectivity and/or chemical noise reduction. The second scenario proposes the use of such modern chemical instrumentation on fast mobile robots. The hypothesis is that, if the time-response of sensors is reduced as a success from the first scenario, the mobile robots will be able to create quality distribution maps faster.

1.4. References

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Chapter 2

Objectives

The main objective of this thesis is the proposal, development, and validation of new Ambient Intelligence (AmI) systems focused on maintaining and controlling the environmental conditions in human-frequented areas by means of using mobile robot technologies. Specifically, this thesis addresses the use of mobile robot platforms for the gas leak source localization problem under the context of the Spanish Ministry of Economy and Competitivity “Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica” granted projects.

This thesis presents new applications and methodologies in Ambient Intelligence which provides environmental control by using a single mobile robot for an entire area complex. This method reduces the cost of installing sensor networks in large environments and provides adaptability and accuracy to sensing applications. On the one hand, the developed methodologies can be exported and used in many AmI applications which require the use of mobile robots. On the other hand, the work focused on the gas source localization problem provides new perspectives, basements, and methods to address the problem in a more informed way.

The specific objectives of this PhD Thesis are:

- Design and develop a distributed control system for a mobile robot capable of engaging different mobile robot agent functionalities in the same computational unit without decreasing global performances. Navigation, mapping, decision making, computer vision, and sensor management are some of such robot functionalities that have to be executed simultaneously as well as engage an effective information exchange among them.

- Implement a first AmI application based on controlling the environmental conditions of an office area by mobile robot patrolling. This methodology has to provide reliable and localized sensor information in order to detect possible anomalies and discrepancies which will used to apply corrective ambient actions.
- Perform an exhaustive analysis of the gas diffusion behavior in a controlled environment in which the environmental conditions such as temperature, wind intensities, and gas injection rate can be adjusted. For a better interpretation it is proposed the creation of gas and wind distribution maps from sensor datasets captured in real experiments.
- Develop and perform an experimental planning for gas leak source localization in different real indoor environments. A mobile robot has to be prepared for patrolling in different areas and capturing sensor samples while moving. Results must show the map of the area created by the SLAM methodology and the localized values of the sensor samples. Such conclusions will be considered to develop reactive and non-reactive search algorithms for mobile robots.

Chapter 3

PhD Thesis structure

The development of this PhD Thesis has been performed in the Robotics and Signal Processing Research Group associated with the INSPIRES UdL group (Institut Politècnic d'Innovació i Recerca en Sostenibilitat, centre de recerca de la Universitat de Lleida). This thesis has been partially funded by the Spanish Ministry of Science and Innovation granted projects: TEC2011-26143 and TEC2014-59229-R, by Iberdrola Foundation through its Call for Research on Energy and the Environment, by the Recercaixa 2013 research grant, and by the Government of Catalonia (Comisionat per a Universitats i Recerca, Departament d'Innovació, Universitats i Empresa) and the European Social Fund.

This PhD Thesis is structured in four chapters corresponding to for four published papers; according the Science Citation Index (SCI) one of the journal is classified as a Q1 journal and another as a Q3 journal. The other two journals are indexed as Q4 in the Scimago Journal Rank (SJR). Figure 3.1 shows the structure of the PhD Thesis. The referenced papers are:

- Martínez, D.; Clotet, E.; Moreno, J.; Tresanchez, M.; Palacín, J. A Proposal of a Multi-agent System Implementation for the Control of an Assistant Personal Robot. Advances in Intelligent Systems and Computing (SJR as Q4) 2016, 473, 171-179.

- Martínez, D.; Teixidó, M.; Font, D.; Moreno, J.; Tresanchez, M.; Marco, S.; Palacín, J. Ambient Intelligence Application Based on Environmental Measurements Performed with an Assistant Mobile Robot. Sensors (SCI as Q1) 2014, 14, 6045-6055.

- Martínez, D.; Moreno, J.; Tresanchez, M.; Clotet, E.; Jiménez-Soto, J.M.; Magrans, R.; Pardo, A.; Marco, S.; Palacín, J. Measuring Gas Concentration and Wind Intensity in a Turbulent Wind Tunnel with a Mobile Robot. Journal of Sensors (SCI as Q3) 2016, 1–8.
- Martínez, D.; Pallejà, T.; Moreno, J.; Tresanchez, M.; Teixidó, M.; Font, D.; Pardo, A.; Marco, S.; Palacín, J. A Mobile Robot Agent for Gas Leak Source Detection. Advances in Intelligent Systems and Computing (SJR as Q4) 2014, 293, 19-25.

The chapters represent the different perspectives faced to develop an autonomous mobile robot capable of performing different AmI tasks giving a special importance to the gas source localization problem. As the first work (chapter 4), this thesis proposes a methodology to implement a high-level control system of a mobile robot by means of using a multi-agent architecture that provides versatility, effectiveness, and robustness among different robot processes. A more specific application for a mobile robot agent is presented as the second work (chapter 5) which proposes the use of a mobile robot to perform autonomous environmental measurements in order to detect and localize ambient anomalies. The two last papers specifically addresses the gas leak source localization problem providing an accurate area characterization (chapter 6) in a custom wind tunnel and field experimentation and results on different real indoor environments (chapter 7).

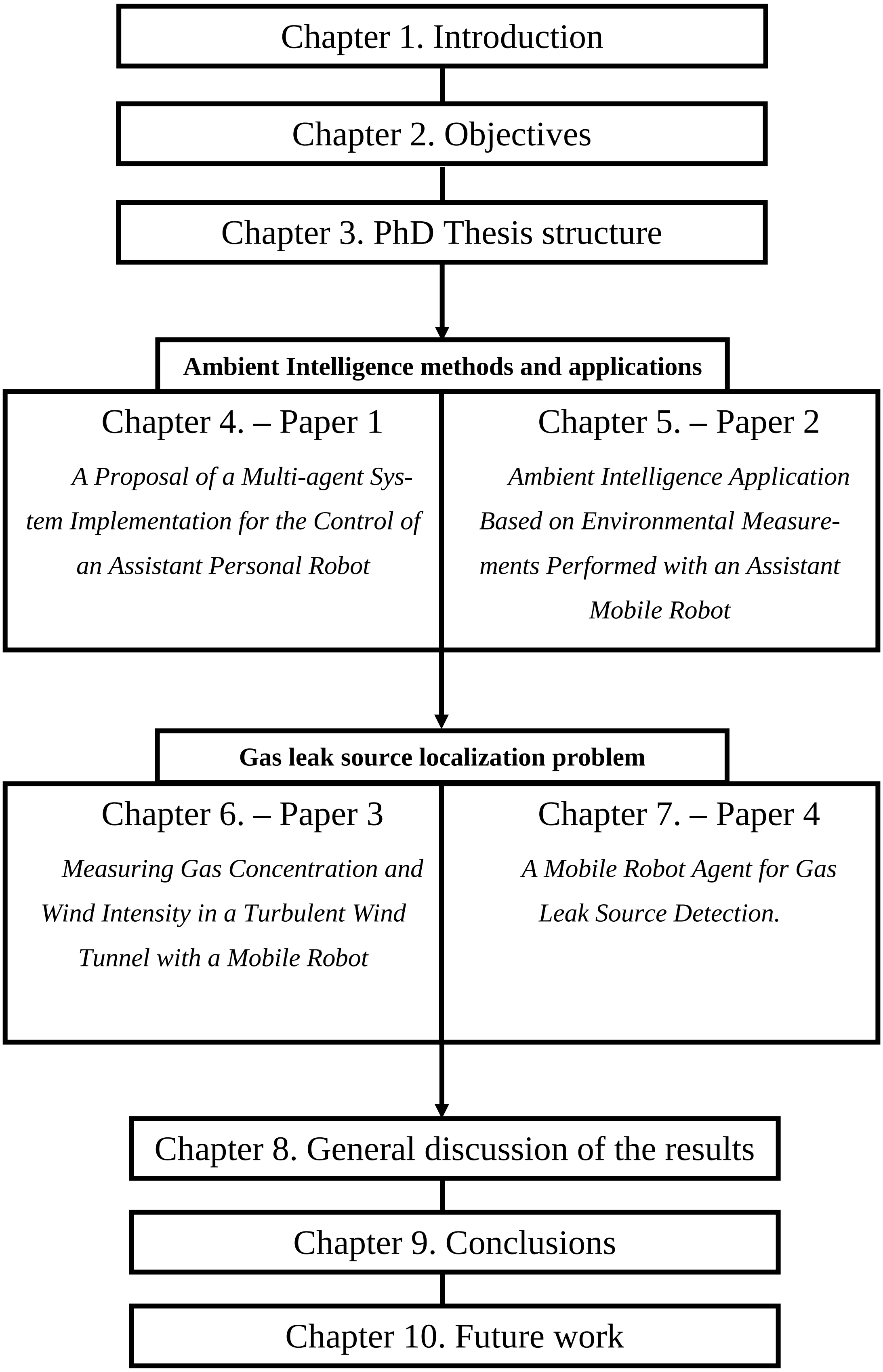

Fig. 3.1. PhD Thesis structure

Chapter 4

A control system for a mobile robot based on a multi-agent architecture

4.1. Introduction

This chapter proposes the design and implementation of a mobile robot control system based on a distributed multi-agent architecture. The paper presented in this chapter proposes and describes a new control system used in an Assistant Personal Robot (APR) in order to manage the different dynamic robot features among different distributed logical control units.

The design and the distribution in a logic scheme of the different functionalities required to provide final robot services is considered a critical point to deal when developing complex control systems for robots due to its direct relation with the system global performance and capabilities. Furthermore, having an adequate logical design of a control system for a robot is not the only problem to solve; the hardware architecture of a robot computational unit has also to be taken into account as well as possible installed low-level software such as an operating system. A good cohesion among the different layers between the control system and the hardware is essential to achieve satisfactory levels on robot service performance.

4.2. Contributions to the state of the art

Research on new designs, architectures, or paradigms for robot control systems has not been widely addressed in a global perspective. However, there are many proposals on control systems that handle specific robot functionalities such as the work presented in [1] which uses a hybrid logic control design for robot localization, mapping and navigation with satisfactory results. In a similar way, [2] used the Microsoft Robotics Developer Studio framework to implement a high level control system for autonomous navigation based on a service oriented architecture.

In a lower level, [3] proposed a control system for an industrial robotic arm which uses an embedded FPGA platform. The ASEBA architecture [4] provides an event-based modular control system for microcontrollers in order to allow the implementation of complex behaviours in robots. An example of a more complex control system is applied in [5] for a rescue robot engaged with a Hierarchical Reinforcement Learning for autonomous decision making.

In this PhD thesis has been realized other related research in this field as the journal paper published in [6] which proposes a smartphone-based control system for soccer mobile robots (Fig 4.1.). In this implementation the mobile robot takes profit of the powerful smartphone processor and other embedded features such as the accelerometer, camera, and USB connections to engage a communication with an external motor control board.

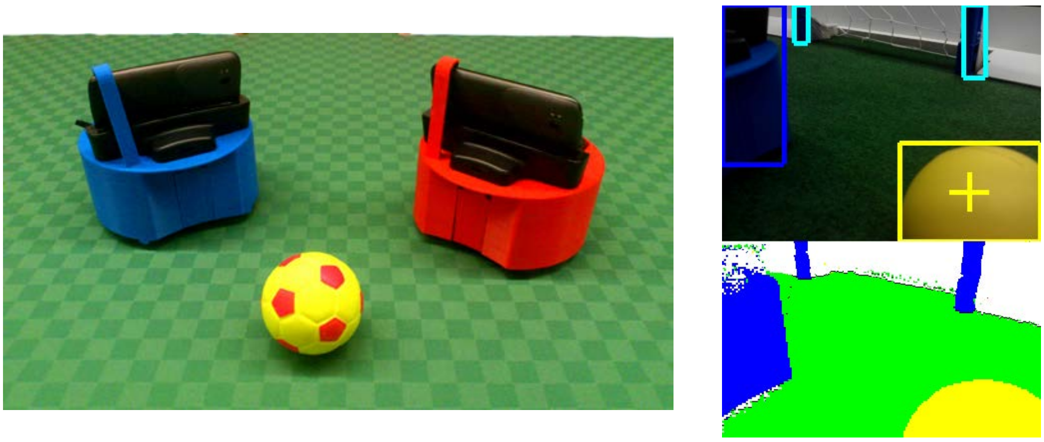

Fig. 4.1. Smartphone-based mobile robots (left) and its vision system (right), reproduced from [6].

The control system of such proposal is based on a multi-threading architecture integrating decision making, motor control, and computer vision processes. The computer vision algorithms are implemented by using the RenderScript framework for Android which speeds up its computation by parallelizing work across processor cores and the GPU. Results show that the robot detects all the important elements in the playfield and its captured parameters are used to engage a robot soccer game.

The paper presented in this chapter propose the use of a multi-agent architecture for a robot control system to set up the different required processes in an effective design. This multi-agent system is composed by independent robot processes such as navigation, localization, decision making, computer vision, communications, voice recognition, and sensor acquirement. Several shared memory instances are implemented in order to allow a constant communication among the different processes. External devices attached at the robot (sensors and actuators) only can be exclusively accessed by one agent process, so, it is not necessary the use of any semaphore-based system. In this proposal, each of such processes are assigned to be executed in a single hardware thread in an new-generation Intel® Core™ i7 processor which has up to 8 execution threads.

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Martínez, D.; Clotet, E.; Moreno, J.; Tresanchez, M.; Palacín, J. A Proposal of a Multi-agent System Implementation for the Control of an Assistant Personal Robot. Advances in Intelligent Systems and Computing (SJR as Q4) 2016, 473, 171-179.

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ISSN: 2194-5357

Chapter 5

Development of a mobile robot for environmental monitoring as an AmI application: methodology, application, and validation

5.1. Introduction

This chapter presents an Ambient Intelligence (AmI) application based on achieving an adequate maintenance of a healthy and a comfortable human ambient in workplaces by using a mobile robot. This chapter presents a paper describing a methodology proposed to develop a mobile robot platform capable of patrolling indoor office areas while gathering sensor lectures of its surrounding environmental conditions in order to detect and localize an ambient anomaly.

During the last decades there has been published many papers on AmI systems proposing new methodologies, technologies, devices, frameworks, etc. which are getting closer to global public everyday lives especially with the emergence of Ambient Assisted Living, smart cities and Internet of Things. Most of AmI systems are designed to autonomously offer embedded services in order to ease and improve human-related tasks in a defined environment. Maximizing the adaptability and minimizing the intrusiveness are good guidelines when designing and developing such systems. The main advantage of using mobile platforms is that they provide mobility for developing its tasks, thus, they improve the adaptability of an AmI system. Unlike sensor networks, this solution saves the cost of installing fixed distributed devices in a delimited area which can become unaffordable on big environments.

5.2. Contributions to the state of the art

Current scientific contributions on AmI systems face different problems under different contexts. For example, a popular addressed problem is to optimize the energy consumption by providing intelligent systems like in the work presented in [1] which describes an AmI system based on wireless sensor networks for smart buildings. Human comfortability is also an important subject in AmI systems, for example, [2] proposed an assisted sleep system by sound adjustment to heartbeat and respiration rates. The combination of different embedded agents in a human environments was already addressed years ago [3], however, the integration of mobile robots is a challenging and more novel motivation in AmI environments. Robotics was popularly applied for its use on emergency situations such as firefight [4], earthquake rescue, exploration in toxic environments, and bomb defusing. Actually, assistant robots are becoming popular especially in scientific research offering a lot of challenges on providing adaptability, independence, and capabilities. An example of a recently developed assistant robot for our research group is described in [5] which was designed for elder AAL. In addition, co-adaptation among heterogeneous robots in a single AmI environment is an incoming problem which is conceptually studied in [6].

The paper presented in this chapter proposes a novel AmI methodology for the control and prevention of unhealthy ambient conditions in human-frequented environments, specifically, in a workplace building. This method uses a mobile robot to gather localized sensor lectures of environmental parameters according to Heating, Ventilation and Air Conditioning (HVAC) systems. The robot is capable of performing an itinerary of indoor explorations by using a laser range sensor and a SLAM procedure (fig. 5.1). The abnormal situations on ambient conditions are detected, localized, and considered to perform an adequate corrective actuation.

Fig. 5.1. Mobile robot taking ambient measurements while patrolling.

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ISSN: 1424-8220

Chapter 6

Characterization of an indoor environment for gas leak source localization with a mobile robot

6.1. Introduction

This chapter describes a more complex problem which consists on finding the source location of the detected ambient anomalies in an indoor environment by using a mobile robot. Specifically, this chapter addresses the gas source localization problem by a first exhaustive study on the environmental factors that affects when solving this problem in indoor areas. The characterization of an experimental area for gas source localization is proposed in order to extract information, conclusions and directives which will be used for the design of reactive and non-reactive robot search algorithms.

The modelization and characterization of the behavior of a gas agent is a complex problem to face due to its time varying chaotic diffusion which is also affected by several other environmental factors involved in. Wind, gas injection rate, and area shape are some of those important factors that mainly affects to the gas diffusion behavior. Performing a careful an exhaustive setup for the characterization of an experimentation area for gas source localization is required in order to obtain high fidelity levels on results. Finally the results may show whether is any clear plume to follow or there is a better heuristic to take into account.

6.2. Contributions to the state of the art

During the last years, several research works have proposed the modelization of gas distribution maps created from real sensor information. As an example, [1] described a methodology for gas distribution mapping at outdoors by using an aerial drone robot equipped with a CO_2 sensor. In [2] was firstly introduced the use of a Tunable Laser Absorption Spectroscopy (TDLAS) sensor on a mobile robot for 3D gas distribution mapping. A scenario with more than one chemical agent is presented in [3] in which the gas distribution maps are created by combining different non-selective sensors and by applying the Kernel DM+V algorithm. Multi-robot systems are also used for gas distribution mapping applying swarm-based collaboration algorithms in order to optimize the sensor-gathering exploration step [4], however, in some cases information fusion is also required.

Performing a characterization of an experimental environment is very useful for acquiring knowledge from the behaviors of the involved agents. For example, [5] described a methodology to create a measurement dataset from sensor arrays installed in a turbulent wind tunnel in which several chemical agents are released under different ambient conditions. In the scope of this thesis, a first set of preliminary experiments were performed in [6] which results show the relations between ambient conditions and gas concentration behaviors on different spatial points.

The paper in this chapter presents the next work in which an accurate methodology is proposed to create reliable gas and wind distribution maps of an experimentation area focused on gas source localization. The experiments are carried out in a controlled wind tunnel capable of producing a turbulent wind effect by means of four adjustable extractor fans. The methodology consist on using a sensor-enhanced mobile robot to perform a semi-random exploration pattern by at least 60 minutes inside the experimentation area. The time-varying sensor lectures are grouped by divided spatial areas for an accurate and effective posterior analysis of the results.

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Martínez, D.; Moreno, J.; Tresanchez, M.; Clotet, E.; Jiménez-Soto, J.M.; Magrans, R.; Pardo, A.; Marco, S.; Palacín, J. Measuring Gas Concentration and Wind Intensity in a Turbulent Wind Tunnel with a Mobile Robot. Journal of Sensors (SCI as Q3) 2016, 1–8.

http://dx.doi.org/10.1155/2016/7184980
ISSN: 1687-7268

6.5. Additional methods and results

This section shows methods and results from additional related experiments carried out in this chapter for the following published paper:

- Martínez, D.; Clotet, E.; Tresanchez, M.; Moreno, J.; Jiménez-Soto, J. M.; Magrans, R.; Palacín, J. First characterization results obtained in a wind tunnel designed for indoor gas source detection. In *IEEE International Conference on Advanced Robotics (ICAR)* **2015**, 629-634.

6.5.1. Evaporator system

The evaporation system used in the experiments is based on a KDS model 200 syringe pump by KD Scientific Inc. and a conventional welder for electronics attached to an aluminum plate. This setup allows to configure a specific drop rate in µl/min by the syringe pump which are instantly evaporated by the aluminum hot plate (fig 6.1). The only drawback of this system is the capacity limitation of the syringes which could not be enough for high concentration experiments. However, in this thesis are proposed other less-precise gas evaporator mechanisms that allows the evaporation of larger loads.

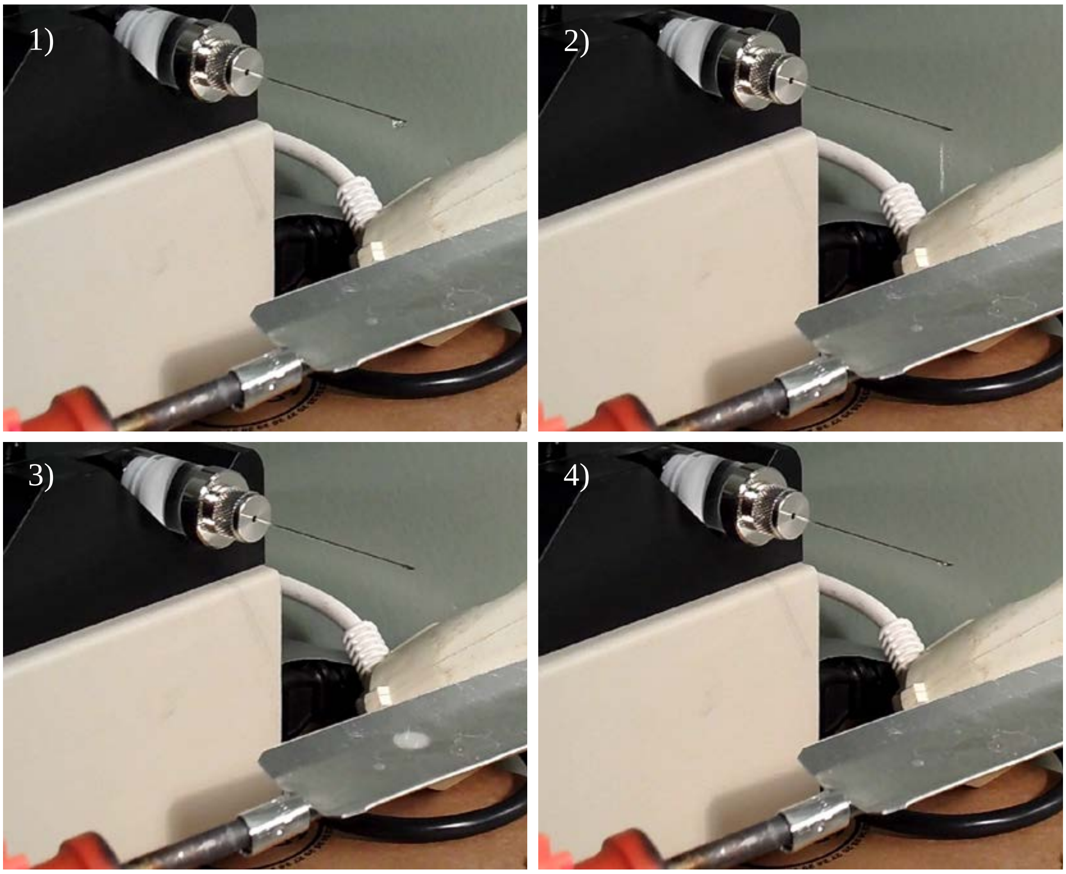

Fig. 6.1. Gas evaporator system based on a syringe pump and a welder. 1) The syringe pump applies a constant and a controlled pressure to the syringe. 2) The acetone accumulated at the needle of the syringe finally falls as a drop. 3) The acetone drop touches the aluminum hot plate and gets warm. 4) The acetone is completely evaporated and the process starts again.

6.5.2. Smoke test on wind tunnel

In this thesis the wind diffusion patterns have been validated by means of different smoke tests. Figure 6.2 is composed by four key pictures taken in few seconds when performing a smoke test. The images show the evolution of the experiment: 1) The tunnel is clear and the smoke is just released; 2) A first defined smoke plume appears in the tunnel; 3) The smoke is getting diffused in the whole tunnel but the main plume seems that is going through the left side; 4) In this last observation the smoke is about to became opaque but the plume tendency is confirmed. So, the test reveals that the wind flow tends to deviate through the left side of the wind tunnel, thus, the accumulation of the gas agent in such area is less than the other locations.

Fig. 6.2. Image captures from the smoke test on the wind tunnel.

Chapter 7

Experimentation and results on gas leak source localization in real indoor environments

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7.1. Introduction

This chapter presents several experimental scenarios on real indoor environments for gas source localization with a mobile robot. The methodology for robot gas source localization is described through several scientific works published in the scope of this thesis. As well as in robot-based AmI systems, this methodology is flexible and adaptable to any environment without requiring specific infrastructures or installations. However, the different environmental conditions found across the area may cause unexpected behaviors on gas diffusion. So, the complexity of the problem forces to adopt flexible heuristics as well as gather more information from other involved environmental agents.

This application was originally conceived to avoid exposing humans to potentially hazardous environments by using mobile robots instead. In robotics, is easy to find similar applications in which robots operate in dangerous places having as objective the search for something or someone, and the realization of a specific task. In the literature most of robot search algorithms used for gas source localization are popularly based on nature agents which are called bio-inspired algorithms. In this specific problem such algorithms take references from highly odor-sensitive animals such as the moth, the dung beetle, and others. A popular approach of these proposed algorithms is focused on detecting a gas plume and then try to follow it until reach the source like pheromone following. In this thesis this kind of search algorithm are also called reactive search algorithms.

7.2. Contributions to the state of the art

The effectiveness of gas source localization methods has been discussed specially during the last decade by several approaches, experimental setups, and sensor configurations. First approaches on gas-sensing mobile platforms were presented in mid 90s providing first discrete contributions on this field [1,2]. During those years it was firstly proposed the use of natural behaviors for gas source localization. Specifically, [3] proposed the imitation of the pheromone tracking procedure of a male silkworm moth. Along the 2000s several improvements and similar approaches were proposed. For instance, another novel bio-inspired search algorithm was presented in [4] which was based on resetting spiral displacements when detecting gas hits. In early 2010s, the effectiveness of biological inspiration on gas source localization algorithms was discussed in [5] concluding that although animal behaviors can be imitated, actual chemical sensors are not comparable to natural senses. So, they consider that a strict imitation of biological behaviors is not correct to address.

Latest publications on gas source localization faces new experimental setups and platforms such as in [6] which presents a method comparison by using an Unmanned Aerial Vehicle (UAV). On the same line, in [7] is proposed the use of a robot swarm to track a stabilized gas plume in an outdoor scenario. As an alternative focused on industrial environments, in [8] is described an autonomous robotic system for gas leak detection and localization by means of using infrared and thermal sensors instead of chemical sensing techniques.

The paper in this chapter presents a methodology for robot gas source localization and practical experimentation in real indoor environments. The experiments were carried out in different areas from the polytechnic high school of the University of Lleida. The mobile robot uses an SLAM procedure and gathers localized gas and wind information while patrolling across the area in order to extrapolate an approximate localization of the gas source. Results from such real experiments show the effectiveness of the proposed methodologies for gas source localization.

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ISSN: 2194-5357

7.5. Additional experiments

This section shows methods and results from additional related experiments carried out in this chapter which have been published in several scientific conferences.

7.5.1. Source localization experiments

This section shows a brief view on results obtained in specific localization experiments published in [1,2]. Fig. 7.1 and Fig 7.2 show the mobile robot trajectory and the gas concentration measured during the exploration. Both experiments were based on similar exploration methods but were carried out in different featured areas: in a small office room, and in a large hall of the faculty. In both cases a custom gas evaporator was placed near a wall in the experimentation areas in order to simulate an accidental gas leak. Results have shown that the localization of the gas leak in the case of no turbulent airflow can be achieved by using non-reactive localization procedures.

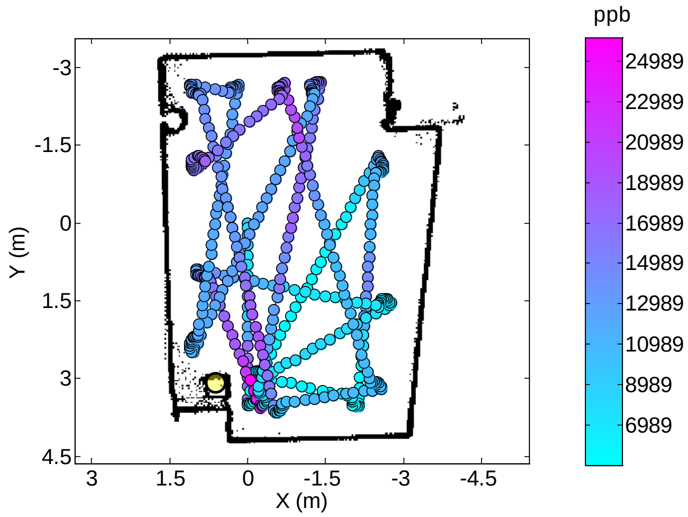

Fig. 7.1. Mobile robot trajectory and gas concentration obtained in an office. © [2014] IEEE

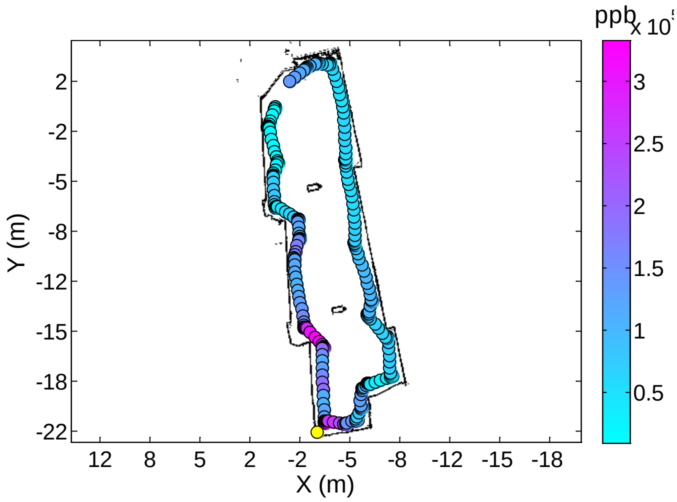

Fig. 7.2. Mobile robot trajectory and gas concentration obtained in a large faculty hall. © [2014] IEEE

7.5.2. Use of an Ion-Mobility Spectrometer

The incorporation of an Ion-Mobility Spectrometer (IMS) in a mobile robot enables the development of tasks such as multi-gas source localization (fig. 7.2) because the IMS is capable of discriminating different odors. The methodology applied to evaluate the localization and discrimination performances of an IMS was based on the realization of a set of experiments focused on detecting and localizing two different gas sources in a controlled experimental environment. The localization of the gas sources was computed by a recursive algorithm that generates and updates probabilistic maps while the robot is patrolling the experimentation area. Acetone and diethyl ether were used for the experimental setups which were released at the same time and with a similar evaporation intensity. The description of the experiments and the discussion of the results obtained have been published in [3].

Fig. 7.3. Mobile robot with an IMS as a main chemical sensor device.

7.5.3. Application of bio-inspired search algorithms

The trajectory control algorithm of a mobile robot based on the information obtained by a gas sensor is a perfect candidate for the application of bio-inspired reactive search algorithms. The complete proposal, implementation and results obtained has been published in [4]. This proposal uses only the information of the measurement of the gas concentration in order to define the trajectory of the mobile robot and future implementations will include wind heuristics in order to save time by means of a better informed search. The proposed algorithm temporally stores gas concentration values which are compared and used to determinate if the robot has to go straight (during 0.5m) or has to turn right 90 degrees. Other cases and constraints have been also considered, for example when the robot is forced to vary its direction due to the presence of obstacles and the prevention of infinite loops. Fig. 7.4 shows the mobile robot trajectory when executing the proposed bio-inspired algorithm in a wind tunnel. In all cases tested, the mobile robot was able to localize the gas source independently of the initial position and orientation of the mobile robot.

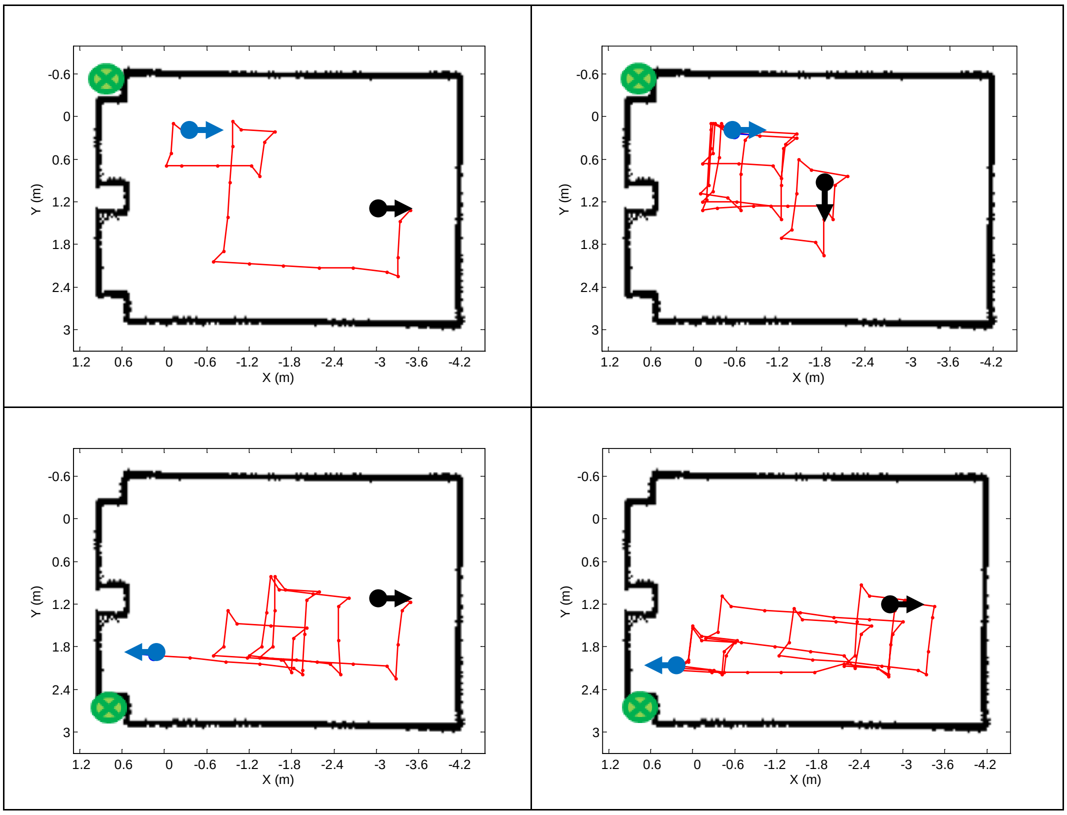

Fig. 7.4. Mobile robot trajectory obtained with the proposed bio-inspired search algorithm. The black arrow depicts the robot initial position and the blue arrow depicts the final one. The gas source is marked as a green circle and the robot trajectory is the red line.

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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. A control system for a mobile robot based on a multi-agent architecture

The results discussed in this section corresponds to the results presented in the paper "A control system for a mobile robot based on a multi-agent architecture" described in chapter 4.

This proposal describes the control architecture of a mobile robot based on a multi-agent design composed by several agents which are focused on performing specific robot functions. Such agents are designed to work independently from the others but the exchange of information between them is required to achieve an optimal effectiveness which is performed by means of shared memory instances. The access to the hardware devices connected to the robot is limited to a single agent in order to avoid performance problems but is enabled the possibility of sharing such information on the instances if any other agent needs to use it.

An APR was used as the robot platform for the validation of the proposed multi-agent control system. The main features of the mobile robot computational unit are: Intel Core i7-6700 3.40GHz processor, 16GB of DDR4 memory and a solid state drive hard disc. The motion orders of the mobile robot are processed by an external motor control board managed by an ARM-based processor that senses wheel velocity and generates the adequate motor control signals. The main processor can enable 8 execution threads in its 4 physical cores which are managed by the operating system. The different agent processes are assigned to be executed in individual execution threads in order to isolate them from performance disturbances, so, this system can have up to 8 agents being executed simultaneously. For the proposed experiment the whole multi-agent system was executed and the agents were fully operational. The average computational load of each execution thread was measured by the operating system and the performance and effectiveness of this method was discussed. Results showed that the most demanding task is the SLAM procedure but, even in this case, without reaching the 100% of load. Tests performed with this configuration show that the mobile robot offers robustness and an effective coordination among the agents. In addition, test results showed no irregular delays or other unwanted effects.

Future work will be focused on the development of additional assistive robot routines for the proposed control system in order to provide a more complete APR service.

8.2. Development of a mobile robot for environmental monitoring as an AmI application: methodology, application, and validation

The results discussed in this section corresponds to the results presented in the paper “Development of a mobile robot for environmental monitoring as an AmI application: methodology, application, and validation” described in chapter 5.

The methodology described in this chapter is based on the use of the sensing capabilities of a mobile robot for environmental monitoring in order to preserve a comfortable and healthy ambient condition for humans. The proposed experimental scenario is a 42 meter length corridor with small office rooms along. For this experiment, the mobile robot was configured to follow the wall on its left until reach the end of the corridor. In addition, the robot was able to enter into office rooms in cases where its door was open enough. An SLAM procedure was implemented in the robot in order to create the map of the supervised area and to accurately localize each wind, temperature, and gas measure performed. During the experiment, the HVAC of an accessible office room was switched off and the other accessible room was still operational.

Results from the exploration experiment show two value peaks on temperature measurements that matches when the mobile robot enters and leaves into the office rooms. When the robot just enters the first room with the HVAC system enabled, a signal peak is detected on the embedded thermometer that just starts decreasing when going to the occupancy place of the office room. When returning to the room entrance, the temperature increases again until totally leaving the office room. Information from wind intensities and orientation does not reveal any abnormal condition having an average wind speed of 0.2 m/s. Gas samples show a signal increase when entering the office room but still remains so far from being harmful for humans. The irregular temperature profile of the office room has promoted an ambient actuation by analyzing physical features of the room which can determine the circulation of the hot air.

A further measurement experiment was proposed in order to verify the formulated hypothesis about hot air circulation in the office room. Four temperature sensors were distributed in four strategic locations in order to extract more information about this problem. Furthermore, corrective actuations were performed and its effectiveness were validated by new measurement tests.

The proposed methodology provides an autonomous system to detect ambient anomalies with the recompilation of accurate and localized sensor measurements. This system also allows having a solid background of information when performing the corrective actuations. Future work will be focused on the estimation of energy saving, occupancy comfort improvement, and development of predictive thermal models by using the proposed methodology as a research starting point.

8.3. Characterization of an indoor environment for gas leak source localization with a mobile robot

The results discussed in this section corresponds to the results presented in the paper “Characterization of an indoor environment for gas leak source localization with a mobile robot” described in chapter 6.

This chapter presents a methodology to perform an accurate characterization of a real experimentation area for gas source localization by creating gas and wind distribution maps. The experimentation area was a custom-build wind tunnel of 3.5 m (width) x 4.8 m (large) x 1.8 m (height) as inner dimensions. The measurement platform was a mobile robot capable of moving across the wind tunnel and was equipped with a Photoionization Detector (PID), an anemometer, and a laser range sensor. The methodology to create information maps is based on grouping time-varying measurements into designed spatial areas inside the global experimentation area. Such grouped information is further statistically computed to show their local maximum, average, and standard deviation. The experimentation stage is divided in two sections: the wind profile and the gas distribution profile. The wind profile section proposes three experimental configurations in which the fan powering was set at 33%, 66% and at 100% to create a turbulent wind condition inside the tunnel. Results from this section show the wind plume through the center of the area with different intensities and for each statistical view. The gas profile section proposes four experimental cases in which the wind intensity and the emplacement of the gas source is modified. In the first case the gas source is placed on a corner of the wind tunnel and the fan power is set to 33%. Case 2 has the same configuration as the previous one except for the fan powering that was increased to 66%. For the case 3 the gas source was placed at the center of the tunnel just below the pushing fan which was at 33% as the others. In case 4 there were two gas sources placed on the two corners of the same wall and the fans were at 33%.

Results from each four experimental cases are analyzed as well as for each statistical view of them. The information layers from case 1 shows high concentration areas at the same side of the tunnel where the gas source was placed. Case 2 layers shows similar results from case 1 but the area is smaller and near the location of the gas source. Case 3 results shows a uniform diffusion of the gas agent along the wind tunnel without a well-defined gas plume. Gas distribution maps from case 4 shows high concentration levels along the whole tunnel but the highest peaks are detected near the locations of the gas sources. According to this results, the local maximum seems the best option for implementing heuristics on gas source localization algorithms.

Future research will use the conclusions extracted from this chapter to propose and develop autonomous gas source localization frameworks.

8.4. Experimentation and results on gas leak source localization in real indoor environments

The results discussed in this section corresponds to the results presented in the paper “Experimentation and results on gas leak source localization in real indoor environments” described in chapter 7.

This chapter presents several experimentation setups for gas leak source localization performed in real indoor environments frequented by humans. An own-made mobile robot equipped with a Photoionization Detector (PID) and an anemometer is used for the experiments. The mobile robot has been programed to explore along the experimentation areas at an average speed of 0.6 m/s and to perform SLAM at the same time. Gas concentration and wind measurements are taken at 1Hz and stored for further analysis on gas source localization as a non-reactive search procedure.

Three different scenarios were proposed to carry out the experiments: a large corridor, a main hall, and an office room. The gas source was placed at the center of a 42 meters long corridor for the first experiment, in addition, wind conditions were rather soft in the whole area. Results show a sharp increase of high concentration levels when passing near the gas source which is decreasing progressively when the robot goes away as the same direction as the wind. The next experiment was carried out in the main hall of our faculty where an acetone evaporator was placed on a corner and where wind speed intensities show very low levels. The mobile robot is prepared to enable an exploration procedure based on following its right wall until performing a complete round in the area. Results show a similar behavior as the previous experiment having a discrete area of the highest gas concentration levels near the acetone source. However, this experiment revealed an unexpected second source of a similar gas coming from the door of the mechanics laboratory. The third experimental setup is localized in an office meeting room with two domestic fans in order to generate a simulated airflow. Four experimental cases were carried out in such environment in which the location of the gas source is modified. The mobile robot has implemented an exploration procedure based on a semi-randomized walk by performing 12 wall-to-wall displacements inside the room. Results from such cases show similar tendencies as the previous experiments, nevertheless, cases where the gas source is placed with a direct exposition of the airflow produces a more expanded highest gas concentration area similar to a plume.

The localization of the gas source is obtained by computing the center of mass (or centroid) of the samples from the areas with highest gas concentration levels which have been selected by applying a relative threshold. This procedure provides less than 1 meter of error when localizing the gas source in all described cases. Future work will be focused on developing a solid framework based on the automatization of the presented methodologies.

Chapter 9

Conclusions

This PhD Thesis addresses the conception, study, and development of Ambient Intelligence systems and applications based on the use of mobile robots. The proposed applications are mainly focused on environmental supervision of human-frequented indoor areas giving a special importance to the gas leak source localization problem.

The major achievements of this PhD are the following:

- **<u>Multi-agent robot control system.</u>**
  The proposal is the implementation of the control system of a mobile robot based on the design of a multi-agent architecture capable of managing the required operational processes in an autonomous mobile robot. The experimental robotic platform used for this proposal was an APR-02 which was improved with multiple embedded sensors, actuators, and with an integrated computer. The implemented control system uses distributed agents to handle different robot services and devices in an effective statement. Each of such agents have been assigned to be executed exclusively on a single execution thread in order to provide robustness and effectiveness to their overall performance with no irregular delays or inconsistences from the most computational demanding processes. As a result from the implemented methodology, the mobile robot is able to set up the different robot processes: navigation, localization, task manager,

sensor acquirement, communications, face recognition, and voice order detection.

- **Environmental comfortability application.**

  The development of an ambient supervision application based on a mobile robot is proposed as a decentralized and an accurate system to detect anomalies on HVAC and on human comfortability in indoor human working places. The mobile robot is able to patrol in indoor areas, create virtual maps, and get localized by itself. In addition, the onboard sensors attached to the mobile robot constantly gather information from its environment in order to realize a further analysis of the supervised areas. Results from the experiments show that the mobile robot was capable of detecting and localizing a thermal anomaly in a small office room which was further addressed by more focused tests and corrective actuations. As conclusion, this methodology provides a solid basement for an AmI-based application for ensuring a healthy and a comfortable ambient conditions in human environments.

- **Gas source localization problem.**

  The gas source localization problem is addressed by using a mobile robot with embedded sensors. This challenging problem requires a deeper study than a conventional AmI application. This thesis has two chapters based on the gas source localization problem: one chapter proposing an accurate environmental characterization methodology, and the other proposes a non-reactive gas leak source localization methodology with experimentation in real environments.

  The results from the area characterization show detailed gas and wind distribution maps created by spatial-grouped and time-varying measurements obtained from real experiments with a mobile robot in a custom-build wind tunnel. The information layers show the behaviors of the gas diffusion for each different experimental case proposed in the chapter. Results show that the computation of a local maxima of such grouped measurements is the best option to be considered as search heuristics. As an additional observation, the direct exposition of a gas source to a turbulent airflow raises the difficulty of the source localization procedure.

The experimentation on autonomous gas leak source localization was carried out in real indoor environments with different shaping and features. A mobile robot was used for the experiments in which is implemented a non-reactive search algorithm based on performing explorations across the supervised areas while gathering localized sensor samples. Once the robot finishes the exploration, it extracts the areas with the highest gas concentration values by applying a relative threshold. Then, the center of mass (centroid) of such areas is computed and shows the estimation of the current gas source location with an error less than 1m in the proposed experimental cases.

Chapter 10

Future work

This section presents and describes several research branches opened by the results of this thesis that can be addressed as future work. This thesis has been focused on the development of Ambient Intelligence (AmI) applications based on area control and supervision for the maintenance of healthy and comfortable ambient conditions. In addition, all the methodologies presented in this thesis involve the use of a mobile robot as the main experimental tool. This thesis has proposed a control system based on a multi-agent architecture to set up a mobile robot with advanced capabilities. This research sets a basement for further development and integration of complex robot functionalities. So, next steps are expected to be focused on the development of several robot applications on Ambient Assisted Living (AAL) for its integration in a next-generation Assistant Personal Robot (APR) platform. The proposal of this research will be determined, if possible, as a project with the collaboration and supervision of professionals on geriatric nursing.

Further work on the gas source localization problem will be performed according to the schedule of the SIGVOL project. At this point of the project, the signal processing methodologies for chemical detection enhancement are being developed and field experiments are expected to be carried out once having an operational version implemented in the mobile robot. The experiments will be performed in indoor complex-shaped environments with multiple gas sources loaded with different chemicals agents.

Nomenclature

A*	A-star “search algorithm”
AAL	Ambient Assisted Living
ABS	Acrylonitrile butadiene styrene
AmI	Ambient Intelligence
APR	Assistant Personal Robot
ARM	Advanced RISC Machine
CPU	Central Processing Unit
DC	Direct Current
DDR4	Double Data Rate 4
DoF	Degrees of Freedom
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
GPU	Graphics Processing Unit
HVAC	Heating Ventilation and Air Conditioning
I2C	Inter-Integrated Circuit
ICP	Iterative Closest Point
IMS	Ion-Mobility Spectrometer
IoT	Internet of Things
IR	Infrared
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
PID	Photo-Ionization Detector
ppb	Parts per billion
ppm	Parts per million
RAM	Random Access Memory
RFID	Radio Frequency Identification
RGB-D	Red Green Blue Depth
ROS	Robot Operating System
RS232	Recommended Standard 232
SCI	Science Citation Index
SLAM	Simultaneous Localization and Mapping
SSD	Solid State Drive
UPnP	Universal Plug and Play
USB	Universal Serial Bus