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Assistive technologies for the disabled and for the new generation of senior citizens: the *e*-Tools architecture

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Abstract. In this paper we present our exploratory ideas about the integration of agent technology with other technologies to build specific *e*-tools for the disabled and for the new generation of senior citizens. "*e*-Tools" stands for *Embedded Tools*, as we aim to embed intelligent assistive devices in homes and other facilities, creating ambient intelligence environments to give support to patients and caregivers. In particular, we aim to explore the benefits of the concept of *situated intelligence* to build artefacts that will enhance the autonomy of the target user group in their daily life.

Keywords: Assistive technologies, agents, situated intelligence

1. Introduction

The senior citizens represent a fast growing sector of the population in Europe and other developed areas [10]. In an attempt to look for more appropriate solutions to meet the particular needs of this subset of the population, this paper is about envisioning the future use of recent technologies in which software agents, robotics technology, and information networks will be integrated into everyday environments, rendering access to a multitude of services and applications through easy-to-use interfaces, especially designed for the disabled and the senior citizens.

We are clearly thinking of applications that can be circumscribed to well-know, quasi-structured domains (i.e., places with predefined components such as a house, a hospital floor, etc) assuming that they are stable, that there exists enough information about them, and that the environment is somehow able to interact with a computational system (for instance, by providing information to the system). Recent advances in embedded computing and wireless communications make it possible to envision the realisation of the idea of *ambient intelligence*[1] [17], and to put 'intelligence' in

[1] The European Union has already funded some research (*Ambient Intelligence* key action I of the IST FP5, EU Telematics Initiative for Disabled and Elderly people TIDE) to create such an environment with a specific focus on patient-centred healthcare management, the disabled and the senior citizens. The new EU FP6 program explicitly mentions *e*-care and embedded systems as being part of the priority areas of future research (priority thematic areas 1.1.2.i and 1.1.2.ii). Also, in the USA and Japan there is a strong research trend in this line.

every appliance, into the structure of hospitals, homes and, in the long term, even on every street corner [26].

Over the past years, medical applications have successfully benefited from the use of various “intelligent” technologies, such as: Artificial Intelligence (AI), in particular Knowledge-Based Systems, to support practitioners in decision-making under uncertainty [20]; Agent-based technology to model decision-making processes [12,19] with particular emphasis on the information dimension of health care management; and autonomous mobile Robotics to create electric wheelchairs that can navigate autonomously through an environment, just as a robot would do [54]. However, to go beyond partial tools that tackle isolated problems, and into global care and truly assistive services, future applications should be based, on the one hand, on *medical and social understanding* necessary to analyse in depth the problems faced by disabled and senior citizens; and on the other hand, on *new assistive technologies* that can help to face those problems. Assistive technology (AT) must aid disabled and senior citizens in their daily tasks. It can be made possible through:

– Innovative mechanisms by which physical and software agents coordinate sensing, cognition, reasoning, and actuation in well-known environments. Our target population requires that this coordination be done effectively and securely.
– Flexible interfaces supporting the interaction between electrical and mechanical devices and people with a range of capabilities and needs.

The use and creation of new technologies for the disabled is crucial, as for this group of people assistance is not merely a matter of *doing* the same things more quickly or in a simpler way with the aid of a tool. For them, it is a matter of *being able* to perform those tasks independently and, maybe, to learn how to perform new tasks in order to enhance their own autonomy.

The rest of this paper is organised as follows. In Section 2.1 we introduce the problem of disability and give some figures of its impact on society. Then in Section 2.2 we discuss the problems that senior and disabled people have to interact with technological devices. In Section 2.3 we address the issues of safety and soundness that are mandatory in systems integrating various technologies in a single platform. In Section 3 we address the possible uses of assistive technologies in building services for the senior citizens, review some of the current applications and present our own proposals for this field. In Section 4 we envision a feasible (and very appealing) application of assistive technology, presented from the technical, social and healthcare perspectives. Finally, in Section 5, we make some reflections about the future of this technology.

2. Disability and the senior citizens

2.1. Ageing and disability

The ageing of the population today is without parallel in the history of humanity. The increase in the proportion of older persons (60 years or older) is being accompanied by a decline in the proportion of the young (under age 15). Nowadays (2002), the number of persons aged 60 years or older is estimated to be 629 million.[2] This number is expected to grow to almost 2 billion by 2050, when the population of older persons will be larger than the population of children (0–14 years) for the first time in human history. The world has experienced dramatic improvements in longevity. Life expectancy at birth has climbed about 20 years since 1950, from 46 years to its current level of 66 years. Of those surviving to age 60, men can expect to live another 17 years and women an additional 20 years. The number of 80-year old or older people is currently increasing at 3.8% per year and comprise 12% of the total number of older persons. By the middle of the century, one fifth of older persons will be 80 years or older [36].

The increasing number of people affected by chronic diseases is a direct consequence of the ageing of the population. Chronic illnesses, such as heart disease, cancer and mental disorders, are fast becoming the world’s leading causes of death and disability, including the developing world. In fact, according to the World Health Report 2001, non-communicable diseases now account for 59% of all deaths globally. Two examples of highly invalidating diseases requiring medical assistance and/or institutional care are represented by *Alzheimer’s disease* and *stroke*.

Alzheimer’s disease is the principal cause of dementia in the elderly, affecting about 15 million people worldwide. The earliest symptom is usually an insidious impairment of memory. As the disease progresses, there is increasing impairment of language and other cognitive functions. Analytic and abstract reasoning abilities, judgment, and insight become affected. Be-

[2] According to the Second World Assembly on Ageing, Madrid, Spain, 8–12 April, 2002.

havioural changes may include delusions, hallucinations, irritability, agitation, verbal or physical aggression, wandering, and disinhibition. Ultimately, there is loss of self-hygiene, eating, dressing, and ambulatory abilities, and incontinence and motor dysfunction. Last stages of the disease usually lead to institutionalisation in some kind of facility specialised to treat such cases. However, this solution not only has a high cost (institutionalisation accounts for more than 66% of the costs associated to people with severe dementia), but also is harmful for the patient, who is placed in a unknown environment with unknown people.

Stroke is the most disabling chronic condition. It has this dubious honour due to the effects of stroke impact on virtually all functions: gross and fine motor ability, ambulation, capacity to carry out basic and instrumental activities of daily life, mood, speech, perception and cognition. Stroke represents a heterogeneous category of illness that describes brain injury, usually sudden (e.g., haemorrhages, vasospasms, thrombosis). Therefore, in each case the retraining and adaptation process to neurological handicaps depend on the nature of the underlying anatomic abnormality and not on the cause of such abnormality. About 200 people in 100 000 will have a first stroke every year. Their mean age is about 72 years, and men and women are affected in roughly equal numbers.

In both developed and developing countries, chronic diseases are significant and costly causes of disability and reduced quality of life. An older person's independence is threatened when physical or mental disabilities make it difficult to carry out the basic activities of daily life such as bathing, eating, using the toilet and walking across the room, as well as shopping and meal preparation. One or more diseases can be involved in causing disability; at the same time, a single illness can produce a high degree of disability. Therefore, disabled people are a very heterogeneous group, comprising a wide spectrum of function. This ranges from mild impairment and/or disability to moderate to severe limitations [8]. Moreover, the concept of disability itself is not always precise and quantifiable. To facilitate agreement about the concept of disability, the World Health Organization (WHO) has developed the International Classification of Impairment, Disabilities, and Handicaps (ICIDH-2) and the *International Classification of Functioning, Disability and Health* (*ICF*). The concept of health environmental integration (HEI) has been expanded recently [44,45]. It was originally presented as a framework to study how humans and machines interact and complement each other along the ICIDH-2. Now-a-days, assistive technology therapy is directed at both the person and the environment. The objective is to enhance HEI by using devices to neutralise impairments. By neutralising impairment, there is an expansion of people's potential to enter into, to perform major activities within, and to fully participate according to the structure of the surrounding physical and social environments.

2.2. The interaction of disabled people with technology

According to the National Health Interview Survey (NHIS)[3] 1990 results, more than 13.1 millions American people (about 5.3% of total population) use AT devices to compensate their physical disabilities. Potential benefit of AT in improving functional self-dependency of disabled patients, well known in rehabilitation practice, has been reported in a number of legislative acts in different countries.

In the analysis, design and final creation of disabled-oriented devices, it is mandatory to keep in mind the interface problem, either because of a severe mental or mobility dysfunction or the usual complex relationship among elder people and new technologies [41]. The Rehabilitation Engineering Research Center on Technology Evaluation and Transfer (RERC-TET) (Buffalo, NY, USA) has focused on consumer-identified needs and preferences regarding several categories of assistive technology. According to the classification of Batavia and Hammer [6], 11 criteria have been identified that disabled patients consider important when selecting assistive devices: among others, *Effectiveness*, *Reliability* and, mainly, *Operability* – the extent to which the device is easy to use, is adaptable and flexible, and affords easy access to controls and displays. A listing of product categories which RERC-TET's consumers determined to be in high need of new or improved products comprises:

– Related to wheeled mobility: manual wheelchairs, wheelchair cushions, battery chargers, wheelchair tires, wheelchair tiedowns, and van lifts and ramps.
– Other devices: voice input interfaces, voice output reading machines, portable ramps, and workstations.

[3]This study was co-sponsored by National Center for Health Statistics (NCHS) and National Institute on Disability and Rehabilitation Research (NIDDR).

Fig. 1. An example of modern electric-powered wheelchairs.

The extreme difficulty with which persons with severe disabilities have been taught to manoeuvre a power wheelchair is an example of difficult interaction with AT: 9 to 10% of patients who receive power wheelchair training find it extremely difficult or impossible to use the wheelchair for activities of daily life; 40% of patients reported difficult or impossible steering and manoeuvring tasks; 85% of clinicians reported that a number of patients lack the required motor skills, strength, or visual acuity. Nearly half of patients unable to control a power wheelchair by conventional methods would benefit from an automated navigation system. These results indicate a need, not for more innovation in steering interfaces, but for entirely new technologies for supervised autonomous navigation [18].

Our main objective is to address the needs of the future generation of senior citizens. It is of our belief that this new generation will be technologically savvy[4] and because of this fact will be more demanding.

2.3. Safety and Soundness

Even though the domain of application is restricted to a quasi-structured, *situated environment* where *small* changes may appear but the most important landmarks will remain stable for long periods, this does not change the fact that the domain remains dynamic and therefore *unexpected* changes may arise; therefore, AT systems need to solve these unforeseen situations without entering in malfunctioning states. This implies that these systems need to exhibit an intelligent goal-oriented behaviour and yet still be responsive to changes in their circumstances.

As observed by Fox and Das [19], the use of heuristics or rules of thumb to solve problems seems unlikely to inspire confidence. In this domain, the safety of users imposes bigger restrictions and systems must be extensively tested – possibly off-line – to ensure effectiveness and good performance. Therefore, *safety* should be one of the main concerns in the design of disabled-oriented devices. One possible option is to add a safety management layer in those systems. Likewise, the creation of safety plans is mandatory – procedures and criteria that specify *what* the system is supposed to do when, dealing at the same time with hazardous circumstances and events [19]. This is an open issue that has to be further discussed and that should be included in the new technologies for the disabled and senior citizens, as well as in any agent-based tool for healthcare applications.

3. Assistive technologies

Assistive technology devices can be very useful to provide supportive services to individuals who require assistance with the tasks of daily life. Their use spans not only people with cognitive impairment caused by aging factors but also any disabled and handicapped person,[5] in order to ensure an acceptable level of autonomy. By proposing *substitutes for* (or rather *extensions to*) nursing homes (i.e., Assisted Care Facilities), such assistive devices will help to reduce the patient's dependency on others (even from the psychological point of view), especially regarding daily life routines, and to improve his/her quality of life. Such supportive services are also helpful to the caregivers of those patients. In the patient's home environment, technology may aid non-professional carers (relatives, friends) in their efforts, contributing to lengthen the time spent by disabled and elderly individuals in their own home and to postpone the need for institutionalisation. In the hospital environment, such technologies may lead to a reduction of expenses, as increased autonomy of patients would lead to reduced nursing costs, and to a better use of the time and expertise of qualified nursing personnel.

[4] A promising example that supports this claim is Japan, where nowadays even the elder people in the countryside areas have adapted to technologies such as the last wave of mobile phones, attracted by the appealing services that are provided by Japanese phone companies through their wireless network.

[5] From now on, we will use terms such as *patient* or *user* to refer not only to people with cognitive impairment caused by ageing factors but also to disabled and handicapped people.

3.1. Issues to be solved

Services targeted to disabled people should aim at solving the following problems, which also set open and promising lines of research [6] in this field:

- *Physical Aids*: the creation of devices that aid with medication management, household tasks, and mobility [30] [52]. With respect with this latter problem, particularly important is the elaboration of power wheelchairs that are easily driven by people with mental and physical dysfunctions, and that are capable of autonomously making decisions about *where* and *how* to go with the limited, even noisy inputs from the user and from the environment.
- *Cognitive Aids*: tools that provide support to compensate for declining cognitive skills, e.g., reminders, task instruction, and methods to reduce cognitive effort. This is one of the most thrilling problems to be solved, as it requires a combination of technologies such as devices to monitor the user actions linked to others such as sensors and positioning systems installed in the room, all them interacting through wireless communication.
- *Patient Monitoring*: devices and reasoning systems that recognise the patient's activity using input from sensors placed on the patient to track different body signals, and that learn to detect abnormal situations that recommend to call for assistance. With such devices, residential care facilities could, for example, be provided through intelligent beds equipped with embedded instruments for acquiring only vital parameters (blood pressure, glycaemia, pO2, etc.) and to evaluate pressure at the body-bed interface to prevent pressure-ulcers. A mobile version of the same technology would consists in the creation of a portable device to do the tracking in people that can move within an area. Such portable devices could also interact wirelessly with fixed devices (e.g., attached to the room walls) to monitor the movement of patients inside the room, and to identify behaviours like wandering as a symptom of dementia, or even to detect loss of equilibrium to prevent falls.
- *Decision-making*: reasoning systems that respond to situations and the elder's and disabled's needs by interacting with devices in their normal environment, interacting with patients, or contacting caregivers.
- *Human factors*: interfaces that meet senior citizen's needs and capabilities – motor, sensory and cognitive (see Subsection 3.2.3 for additional considerations on these issues).
- *Adaptation*: integration in some of the above devices of machine learning techniques that allow to recognise the elder's changing capabilities and to tailor the behaviour of the device accordingly.

Solving or reducing the impact of these problems in daily life may ease the health care and social interaction of senior citizens. It may also delay their institutionalisation by prolonging the period of relative independence of individuals.

3.2. Integrating technologies to create intelligent assistive devices

Various technologies seem particularly relevant and promising to provide supportive services for physically or mentally disabled people.

3.2.1. Autonomous agents

Autonomous intelligent agents are capable of "understanding" their environment and of independently determining and reasoning how to use their own resources in order to reach a desired goal [53]. Such agents can be either robots or software programs.

Autonomous Robots are physical agents that perform tasks in the real world autonomously. They differ from classical and industrial robots in that they do not have a fixed sequence of actions previously programmed but a set of possible actions that are chosen to be performed depending on given goals or/and information about the environment. Therefore, autonomous robots present more adaptive behaviour and are capable of dealing with environments that cannot be completely controlled. In this case, *autonomy* is often related to *mobility* [23] and thus, one of the main tasks performed by autonomous mobile robots is navigation. Different techniques are applied to solve navigation problems depending on the different features of the environment, such as:

- Its nature: indoors, outdoors, planetary, underwater, etc.
- The level of control the robot has over it: if it remains stable, if landmarks can be added, etc.
- The information available: whether a map exists or can be built, or if it is unknown, whether changes can be monitored, etc.

[6] A good example is the AAAI2002 workshop on automation as Caregiver [1], which is focused in uses of AI in Elder Care.

A robot interacts with the environment through its actuators and sensors; therefore, navigation techniques also depend on the sensors a robot is equipped with. For example:

– Laser, ultrasonic (sonar) and infrared sensors are used to measure distances.
– Pressure switches, bumpers and infrared sensors can be used to detect collisions.
– Wheel (shaft) encoders and Global Positioning Systems (GPS) help to compute location.
– Vision systems are used to recognise landmarks and targets.

Planning and positioning are two key aspects that must always be solved in any autonomous navigation problem. However, although many research efforts have been undertaken in this direction (see [27] for an overview), few of them have focused so far on disabled or elderly people [32].

Software intelligent agents are entities that interact with a *virtual* environment, obtaining information and exchanging it with other agents. Their reasoning capabilities allow them to do complex tasks such as allocating resources, coordinating the action of heterogeneous systems, or integrating information from different sources. Most of the actual agent-based technologies in medicine could be classified, following [42], as: patient centred information management; cooperative patient management; patient monitoring and diagnosis; and remote care delivery. However, all these applications are centred in the information dimension of the health care management. Until now, in the case of senior citizens or elderly people, applications of software agents have been directed towards the integration in society of this population subset via the use of virtual communities, trying to make Internet technology accessible to them (e.g., [7,15]). This agent-based technology could easily be used to help solve other problems that at a first glance might seem minute but that in reality have a big impact in the quality of life of elderly people. A good example is given by cognitive problems such as trying to remember where the patient placed some item (the *Remember what-but-not-where* issue). In restricted environments such as a house or a hospital, a software agent may help to trace the location of the desired object by keeping track of the *usual* places where this object should be or of the last time it was used and/or placed. This may require a shared memory between the intelligent agents and the environment, in a way that allows the agent to use some pointers in the environment to *remember* how things were the last time without having a complete memory of the whole scenario.

Another important area of application is safety management of technologies applied to health care. The *proactiveness* of software agents could be used to perform an active safety management layer by the introduction of *guardian agents*, as in [19], that in a proactive way look for possible hazards and anticipate an answer or send an alert signal to the manager. For example, an intelligent wheelchair must never obey an order asking it to drive the user to the stairs nor to allow the composition of a plan to do that. However, it may override other conditions if the manager asks for it or in the case of an emergency – i.e., the agent should be able to recognise an emergency state – or to ask for help in the case of an impasse. To do this, it is necessary to build safety plans and to be able to reason about them.

3.2.2. Machine learning and other AI techniques

Other AI techniques can also be applied to solve monitoring and mobility problems in assistive tools for elderly or disabled people. Think of problems such as the need to generate a mobility plan for an autonomous wheelchair to cross a very narrow door or navigate within a narrow and difficult corridor, or the problem of recognising impasse and emergency situations where disabled people are completely lost in their everyday environment. Other difficult states that are related to a certain degree of memory loss could also be faced, such as remembering where objects are located, or where objects were located last time they were detected. Moreover, there is the possibility to learn some new tasks or behaviours to enhance the autonomy and good performance of disabled people moving within a particular environment. AI techniques such as planning, knowledge acquisition and machine learning provide some solutions to such problems. However, given the technological framework envisioned here, in which ambient intelligence will provide sensory systems with large amounts of data and experiences in various formats, Case-Based Reasoning (CBR) seems to be one of the most promising approaches.

The main idea of CBR [22] is to solve new problems by reusing or adapting solutions to similar past experiences – known as *cases* – rather than by building new solutions from scratch. Using CBR, it is also possible to avoid some mistakes made in the past, and to learn from some new experiences as the system is running day after day. A typical problem for which CBR can provide efficient solutions is *planning*. This is a very complex task, since good plans must be sequenced appropriately to ensure: (a) that late steps in a plan do not undo the intended results of earlier steps; (b) that preconditions of late steps in a plan are not violated by the results of earlier ones; and (c) that preconditions of later plan steps are fulfilled before the steps are scheduled. As the number of plan steps increases, the computational complexity of projecting effects and comparing preconditions increases exponentially. In addition, a planner dealing with the real world [13,39] must face the real world's complexity, including the fact that it is in many ways unpredictable, and that time is a limited resource – the time used for planning can reduce the time available for execution. Due to the features described above, CBR can address many of these issues, affording the opportunity to anticipate problems [40], re-planning, adapting old plans to new situations, and recovering or repairing a plan that might fail at execution time [2].

3.2.3. *Affective computing*

Emotions are an essential element of our daily lives and interactions with other people and objects around us. Traditionally, however, technology has been oriented towards supporting, improving or extending human capabilities in physical and "intellectual" (reasoning) tasks, disregarding the affective aspects of human cognition and interactions. This trend has started to change in recent years and a new field, *affective computing* [38], has emerged around the idea of bringing emotions into computing and artefacts to endow them with capabilities such as recognising, expressing, responding to, facilitating, influencing, and in some sense "having" emotions. The potential benefits of integrating elements of affective computing into assistive technology for disabled and senior citizens are wide-ranging, and can be seen from two perspectives:

Improving the emotional state of the user. These users are more prone to experience negative feelings such as loneliness, anxiety, frustration, and (mild or severe) affective disorders, given the increased difficulty they have to carry out daily activities, and the physical and social isolation they often suffer. Assistive technology that effectively *cares* for these users should also be able to recognise and monitor their affective states, respond appropriately to them, and try to elicit positive reactions and feelings from the users.

Using emotions as cognitive aids. Recent findings in psychology and the neurosciences have evidenced the fundamental role that emotions play in other aspects of human cognition, even in tasks traditionally considered as being the sole product of reasoning, such as memory or decision-making [14]. Assistive technology should take into account not only the fact that some of the cognitive disorders suffered by these users can also carry affective impairments, but also that some aspects of emotions can be used to influence and facilitate other cognitive tasks.

Let us briefly illustrate with some examples how these general objectives fit within the research lines outlined in Section 3.1:

- *Patient monitoring*. In addition to monitoring the vital parameters of patients, biosensors can be used to detect negative affect such and anxiety and frustration when trying to solve a task (e.g., [21]).
- *Human factors and adaptation*. Affect-aware interfaces are a key element to achieve natural, user-centred and adapted human-machine interaction that promotes user acceptance. They enhance interaction with users by allowing new tasks such as the development of a user's affective profile related to task achievement, or management of users' emotions through expressive elements – for example, soothing music played as a response to a state of anxiety, software or robotic agents that tailor their responses to the user's affective state (see e.g., [51] as an example of an affective pet robot used as therapeutic tool for the elderly), etc.
- *Cognitive aids*. Emotions often act as a memory biases that can reduce cognitive overload. Examples are phenomena such as mood-congruent retrieval – the fact that one tends to remember better contexts, situations and events experienced under a similar mood – and emotional memories – emotionally loaded memories are longer-lasting than emotionally neutral ones. These types of affective "markers" could be added to memory aid systems (for example, the CBR systems mentioned in the previous section) to make recall processes more efficient and better tailored to the autobiographical history of the user.
- *Decision-making*. Loss of memory is only one of the factors that can hamper efficient decision-making. Another major problem that can be present in disabled and senior patients is the lack of a good reason or motivation to decide between alternative courses of action. As pointed out by [14], emotions play a major role as value systems that make us prefer one alternative to the rest. In the context of assistive technology, emotions could help to support decision-making processes in two main ways. First, recalling or making the user aware of the emotional implications of different decisions (e.g., by using a reasoning or mem-

ory system) might help them select one option in a sensible manner. Second, endowing assistive artefacts with internal motivational and emotional systems could allow them to make (simple) decisions autonomously (in cases when the safety of users is not compromised) in the same way they are used for decision making in autonomous agents and robots (e.g., [11,50]).

3.2.4. *Wireless devices*

Wireless technologies have created a revolution not only in technological achievement but also in social behaviours. Such technologies are daily used to control machines (remote controls), to bring communication to any place (mobile phones, beepers) or to provide services at any location (wireless network connections). The evolution in communication channels (to send and receive the maximum information with the minimum bandwidth use) has also come along with the increased availability of computational power inside small devices (PDA's, laptops, last-generation mobile phones).

Wireless links are usually based either on infrared or on microwaves technologies. The main drawbacks of infrared-based links is that direct visibility is required between the transmitter and the receiver. In addition, resulting speeds are not very high. There are three main technologies for microwave-based wireless communications:

- Wi-Fi (*Wireless Fidelity*) is based on standard IEEE 802.11 for radio transmission in the ISM band (2.4 GHz approx.). It was originally developed for unlicensed applications from 1 to 2 Mbps, but the current specifications (IEEE 802.11b) allow as much as 11 Mbps [37]. It is presumed that future versions will allow up to 54 Mbps operating at 5 GHz. The coverage of this technology is equal to 100 meters in open space, but systems using directional antennae may cover several kilometres. This technology is widely spread and most laptops present a PCMCIA interface to support this technology. Other interfaces (PCI, USB or CompactFlash) are also available.
- GSM (*Global System for Mobile communications*) and GPRS (*General Radio Packet Service*) are operator-controlled services. Available *modems* are usually *dual band* (900–1800 MHz), but some models operate at 1900 MHz. GSM is basically oriented to voice communication, while GPRS provides a transition between GSM and third generation mobiles (3G) and supports data communication from 9.6 to 115 kbps. It must be noted that GSM also support data communication but in a less efficient way (14.4 kbps).
- *Bluetooth* and *ZigBee* technologies provide radio links of short and medium coverage to connect different devices without cables. They operate in the ISM band like Wi-Fi (standards 802.K.1 and 802.K.4 respectively). These technologies support point-to-point and point-to-multipoint connections by sharing bandwidth among several devices in a scheme known as *piconet*. In these cases, bandwidth is controlled by a single unit configured as master. A *piconet* can yield up to seven slave devices. If a larger coverage or a larger number of nodes is required, several *piconets* can be grouped into a *scatternet*. *Scatternets* typically present a hierarchical structure, where several slaves can be multiplexed in time and a master can be slave to a higher priority master.

In brief, currently *Wi-Fi* offers the best performance regarding coverage and speed. However, it presents a high power consumption. *GPRS* yields a low bandwidth and it is owned by mobile phone operators. *Bluetooth* is still under research but presents an adequate bandwidth and low power consumption. All these technologies allow the creation of many applications and services accessible through small, portable devices, easily carried by people from one place to another, and are the basis of some of the solutions proposed in this paper to connect patients and caregivers with their environment.

4. An intelligent wheelchair

The scenario depicted in this section applies almost all the solutions presented in previous sections and it is based on a daily problem. Many disabled people[7] of all ages base their mobility in the use of a wheelchair and some times it is an power wheelchair, usually driven with the help of a mouse or joystick that allows the chair to navigate. However, some disabled people experience considerable difficulties when driving a power wheelchair: common manoeuvres (e.g., exit-

[7] In 1997, there were over 1.4 million wheelchair users of which 75% used manual versions. The remaining 25% used power wheelchairs. Power wheelchairs are used predominantly by people with both lower and upper extremity impairments resulting from cerebral palsy, high-level spinal cord injury, or muscular dystrophy.

ing a room) are not easy; steering commands might not be sufficiently accurate (due to spasticity, paresis or tremor in the upper limbs) and collisions can result; and some target users are unable to use their hands. For this sector of population, the solution is to provide them with *Robotic Wheelchairs* integrating some reasoning capabilities that allow the wheelchair to navigate in areas such as the patient's home or a hospital. Most of the time, navigation could be done autonomously under the guidance of the reasoning module. The Tin Man series of robotic wheelchairs [30] are a good example of this kind of chairs. Similar ideas have been funded by the National Institute on Disability and Rehabilitation Research [35]. A very comprehensive survey of this kind of assistive robotic wheelchairs can be found in [54].

For people with milder walking impairments there are other alternatives such as *Assistive Robotic Walkers*. These devices can be seen as passive robots that can steer their joints, but require a human to move them. Wasson and colleagues [52] have been working in the development of this kind of personal mobility aids. Exactly which capabilities the walker exhibits at any time depends on the wishes and abilities of the user.

We will illustrate our ideas with a robotic wheelchair scenario, as the wheelchair has to show complete autonomy in tasks such as path planning and location in the environment, and at the same time pay attention to the user's needs and requests. Although we are thinking of a controlled situation in a quite well-known environment, structural elements like corridors, rooms, or halls may differ. Corridors and rooms in the same building may for example have a various width, length and illumination sources, as well as different distribution and uses. Therefore some of the main problems to solve are: (a) the interface with the user, and (b) the navigation problem.

4.1. *The interface with the user*

Among other ideal features, a flexible interface should include vocal communication, tactile interaction (e.g., a touch pad), and a shared memory system. Such interface should be able to adapt itself to the abilities of different users to allow them to control the chair and to navigate as smoothly and safely as possible (see Section 2.3). For example, the chair should be able to react to orders like *Stop!*, *Watch out!* or *No!* when executing a given plan.

The main task of this interface is thus to interpret user commands that could be noisy, imprecise and/or incomplete, and to transform them into *plausible* orders and plans (Section 4.2). In most cases, the user might only be able to say *what* s/he wants to do or *where* s/he wants to go (through a voice interpreter or a touch pad), leaving to the module controlling the chair – a software agent – the (far from trivial) task of figuring out *how* to achieve it. The solutions (e.g., plans) elaborated have to be integrated in the environment (via the creation of a shared memory as mentioned previously) for future re-use, and to comply with user preferences. This implies that the agent supporting the interface should have knowledge about the current situation of the world. In [32] different approaches to interfaces are presented.

Other existing approaches to creating interfaces with electric wheelchairs are exploring the use of computing the facial expression of a person to guide the chair and in this way take advantage of the user's non-verbal behaviour [34]. Promising work in progress is also exploring the integration of sensors or electrodes to measure and respond to signals such as *electromyographic* signals (EMG) generated by muscles in motion (jaw, elbow) [31]; *electro-oculographic* signals (EOG) generated by eyes and eyelid muscles [25]; and *electroencephalographic* signals produced by the brain (the cortex) [16], to detect some distinctive neuron activation patterns (such as those active when a patient thinks of moving an arm) and use them as input commands.

4.2. *The navigation problem*

Electric wheelchairs to be used by people with some mild/major physical and/or mental impairments should be able to decide autonomously how to move about in the environment. As seen in Subsection 3.2.1, navigation is a key issue in robotics and it must often be assumed that robots operate in unknown or dynamic environments, particularly since odometry is not precise due to slippage and other factors. Therefore, robots (including robotic wheelchairs) cannot be preprogrammed to pursue a fixed course of action and must rely on on-board sensors to perceive the outer world and react to it dynamically. Sonar sensors are quite popular because, despite their drawbacks, they are light, cheap, fast, easy to process and they yield a long detection range. The navigation problem can be summarised by the following questions: (i) *where am I?* (localisation); (ii) *where am I going?* (goal definition); and (iii) *how do I get there?* (planning). Localisation consists in determining the agent position in a global coordinate system and is typically solved by measurement, correlation and triangulation. It is a difficult task that can be performed either using on-board odometry sensors or external active sensors (i.e., GPS). Most systems rely partially on odometry; however, slippage errors accumulate in an unbounded way. In some cases, no odometric information might be available (global localisation). In dynamic environments, place learning and recognition techniques must be combined for on-board sensor-based localisation. Place learning usually consists in storing the position of discriminating features of the environment (landmarks) [47]. Methods that use active landmarks to calculate object position via triangulation are only feasible and efficient in controlled environments. However, when a mobile agent cannot use on-board sensors, it is necessary to resort to external sensors to locate targets (in particular mobile objects) in a non-intrusive way (e.g., video surveillance). Several vision techniques can discriminate (extract) a mobile object from its background. If the camera moves, either optical flow calculation [5] or parametric estimation methods [43] are required. However, these methods tend to be computationally expensive and real-time implementations of them rely on decreasing either the field of view or the resolution of the image. It is possible to use non-uniform resolution image topologies in order to achieve high resolution only in areas of the image containing the mobile object [49]. If the camera does not move and, hence, the field of view is mostly static, it is simpler and faster to rely on background substraction. The background can be either pre-recorded in the absence of mobiles or extracted by averaging a sequence of several images so that moving objects are not included in such a background [29].

Navigation and planning problems are usually solved together using two main approaches – deliberative or reactive [4]. *Deliberative planning* typically relies on a classical top-down hierarchical methodology where the world is represented and processed according to actions and events in a *sense–model–plan–act* cycle. The main disadvantage of deliberative planning stems from its inability to react fast enough to changing world conditions. It also requires a reliable (and hence complex and computationally very expensive) model of the environment. *Reactive approaches* directly couple sensing and acting [9]. Global action results from interactions among reactive behaviours. Reactive systems deal better with situations involving multiple sensors and (often conflicting) goals, and are more robust in the presence of noise and errors (e.g., malfunctioning components); however, they often fall in local traps. *Hybrid systems* combine deliberative and reactive schemes in order to achieve better performance. Usually, low-level control is performed in a reactive way whereas high-level processing follows a deliberative pattern [4]. Most recent approaches to navigation rely on layered hybrid architectures: deliberative layers propose efficient paths to arrive to a goal, but these paths are tracked in a fast reactive way to handle unexpected situations.

Deliberative, hybrid and some reactive architectures typically need a representation of the environment for navigation. Representations are usually constructed according to either a metric or a topological paradigm. Metric representations reproduce explicitly the metric structure of the environment [33]. Topological approaches [28] aim at representing the environment as a set of meaningful regions so that the map becomes a topological graph. Both approaches are complementary in their strengths and weaknesses, and therefore recent research has focused on achieving hybrid representations. A topological-metric representation can be build either by annotating a topological representation with metric information while it is constructed [24] or by extracting a topological map from a metric one [46]. When a representation is available, conventional path planning techniques such as the A^* algorithm can be used to obtain a path, and reactive layers provide the low-level control needed to track such a path in a reactive way.

4.3. A multi-level architecture

In order to provide proper healthcare management (embedded monitoring and diagnosis functionalities) and to ease the relation of patients with other people and the environment we propose to build an integrated system in which the environment (a home, a hospital) and the people inside it (patients, carers) are connected. This approach integrates Ambient Intelligence (sensors, automatic diallers, automatic cooling and heating system) with the various technologies and AI paradigms previously presented.

Our proposal is to install on top of the hardware of an electric-powered wheelchair a Multi-Agent System (MAS) that controls the behaviour of the chair, monitors the state of the patient and interacts with him/her through a flexible interface that provides more or less assistance in navigation, depending on the patient's individual capabilities. Navigation should be au-

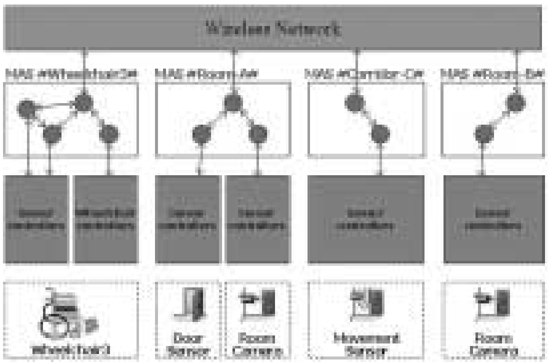

Fig. 2. The proposed multi-level architecture.

tonomously controlled by the MAS most of the time, to relieve the user from tedious low-level decision-making tasks. To make this possible, the wheelchair will be wirelessly connected to the environment. The basic idea is to create active landmarks, that is, small wireless machines installed in some strategic places of an area to transmit local information to the mobile entity. Similar initiatives and ideas can be found in the design of intelligent buildings for disabled and elderly people (see for example [3]) and in the last generation of road traffic support systems. In order to filter all the information received from the sensors and send only relevant information to the wheelchair, each room must be monitored and controlled by a MAS. This agent-based controller can proactively make decisions about room conditioning, or process sensor signals in order to extract meaningful information (e.g., to track a given person in the room).

Figure 2 depicts an example of this architecture. It consists of the following levels:

– The *lowest level* contains all the physical devices that are connected to the environment. This level includes the cameras and sensors attached to the walls, patient monitoring systems, PDA's or other portable devices and intelligent wheelchairs.
– The *second level* comprises the hardware controllers that operate the physical devices and send information to the next level. In the case of complex devices such as wheelchairs or cameras, this level should also perform tasks that might need immediate actions to be taken: for example, in the case of the camera, a behaviour to follow a person that is being tracked; or in the case of the wheelchair, effective obstacle detection and avoidance (*reactive navigation*) to ensure a high level of occupant safety.
– The *third level* is composed of agent-based controllers that receive information from the hardware controllers and combine it with the knowledge they have about the state of the system, to infer *what* information they need to improve their knowledge, *where* to obtain it, and *how* to obtain it. These MAS can also reason about the *relevance* of the information they receive, and distribute it to other agents or controllers that may need it.
– A *wireless network* provides connections among the previous layers. Since not only the patients' wheelchairs but also the environment and other people's portable devices have agent-based controllers connected to the network, interaction and coordination issues can be solved by the software agents.

4.4. *Some representative scenarios*

This type of connection between people and the environment should provide better solutions to some of the problems faced by patients and caregivers. A good example is provided by a small wireless device such as a PDA carried by a caregiver that continuously provides her with information about patients. The same system also allows to route alarms: when a patient enters or is about to enter a dangerous state, the MAS controlling the device detects this fact and broadcasts the message to the PDAs of other carers, depending on the state of the patient. This system may as well send information to the patient's relatives, so that they receive periodic updates about the state of the patient, with the information filtered and adapted to the appropriate level of detail. The situation illustrated by this example could easily be managed by the proposed architecture as follows:

– Initially, either the caregiver generates a request for information on a given patient or the monitoring system detects a hazardous state and generates a request to a caregiver. This request is propagated to the third level of the architecture, where it can be handled by the software agents.
– The third level of the architecture interprets the request and asks for additional information from the lower levels of the architecture to decide a course of action.
– Additional confirmation of the location of either a caregiver or a patient might be requested. In a small wireless network of active beacons, a

given device is captured at most by two beacons so that its position can be inferred by triangulation. If no precise position information is required, this localisation can even be performed by covering each room with a single receiver so that it only provides information about the presence of a given patient or caregiver in the room. The third level of the architecture distributes a request for the position of the caregiver or patient to the first level, which comprises the positioning devices of all rooms.

– If the caregiver has requested information about a patient, a request for low-level information is sent to the appropriate sensors monitoring the state of that patient. These sensors transmit their readings to the nearest node in the wireless network, and the top level of the architecture redirects this information to the petitioner. If a danger situation has been detected, the third level of the architecture classifies the relevant caregivers that have been located according to their proximity to the patient in danger, and a call is transmitted to the closest one.

Patients may also find the system very helpful, for example when trying to go where another person (a relative or a caregiver) is. In the case where that person has the PDA connected to the wireless network, the environment may first locate in which room(s) the patient and the person are.[8] If both are in different rooms, the MAS controlling the wheelchair, using information provided by devices in the environment, builds a plan to go from one room to the other. The wheelchair then executes the plan, carrying the patient to the room where the target person is. If the target person moves from one room to another, the environment forwards this information to the wheelchair, which adapts the plan accordingly. The wheelchair may also report to a human supervisor and ask for help when encountering problems that it cannot handle automatically. This problem is analogous to the previous one.

A more complex scenario is found when the target person does not have a device connected to the system, either because it has been turned off or because it has run out of batteries. In this case, the environment may use other devices such as movement sensors and cameras to locate the target. It is possible to use some knowledge about the target person (size, hair colour, or even the places she usually visits or her patterns of behaviour) to localise that person in the environment. However, this type of recognition is classically a very complex problem unless the problem instance is heavily controlled, especially when the target may be moving in a non deterministic way. Hence, it is easier to keep a history of the position of every possible target in the environment when their devices are off. This way, if a given device is turned off in a room, a video camera in the room starts tracking all mobile objects inside it. If a mobile object leaves the room, networked devices in adjacent rooms can detect whether it is the one with the device off and, in that case, update its position. Using this method, the system can record the position of all unidentified mobile objects available.

The key piece of the system is the patient's wheelchair. In addition to the connection that provides between the patient and the caregiver, the wheelchair enhances the mobility of the patient. Naturally, one of the main advantages of working with a robotic wheelchair is that after the target of a patient's request has been located in the environment, the wheelchair can move towards it in an unsupervised way. To guarantee the safety of the patient and to choose appropriate paths, the wheelchair also receives additional information from the environment (such as the trajectory between the goal and the departing point) provided by the agents in the higher level of the system.

As mentioned in Subsection 3.2.2, planning in the real world is usually complex due to unexpected situations and errors. We propose a hybrid architecture that follows a global plan devised by the MAS in the third level, but this plan is modulated by the reactive modules in the second level of the architecture – that is, the hardware controllers of the wheelchair. This approach (which extends the work presented in [48]) consists of two stages:

1. *Calculation of an efficient trajectory* joining the current position of the wheelchair and its goal. To calculate this trajectory, a model of the environment is needed. This model is typically available in controlled indoor environments, but it is subject to changes if obstacles are not bound to stay in the same position (e.g., small pieces of furniture) or if there are various types of moving agents in the environment . Therefore, the robot must modify the available model of the environment according to its sensor readings. We propose to build and update a metric map of the environment because such maps are easily grounded. However, we extract a topological map from the

[8]Wireless technologies such as Bluetooth support an inquiry protocol to determine if a given node, identified by an unique physical address, is present within its covered environment.

metric one to reduce the cost of the path-planning algorithm so that it can operate in a very fast way. For example, a classic (and rather straightforward) A^* algorithm can be used to extract a path from a topological map. Following this approach, we can recalculate a path each time the goal changes its position, or when it is not possible to track the previous one further. A drawback of the approach is that the trajectory returned is not very precise; however, it is extremely unlikely that the wheelchair would have followed any trajectory in a very precise way in a non static environment and therefore, an optimal path is not required as long as the trajectory joins the departure and arrival points in an efficient way.

2. *Safe tracking of the calculated trajectory* carried out by a reactive system, using for example the well-known potential fields approach. In this approach, the goal acts as an attractor while all detected obstacles in the environment are repulsors. Since the wheelchair already has a trajectory to follow, the points of such a trajectory also act as attractors. Hence, if the wheelchair has to deviate from the trajectory due to an unexpected obstacle in the way, it will tend to return to the path as soon as it has avoided the aforementioned object. At the same time, the map of the environment is updated to show the position of this new obstacle. Hence, if the wheelchair falls in a local trap, we return to the previous stage using an updated map.

The system we have described is designed to be used not only in a hospital, where professional caregivers are present, but also in the patient's home, where usually relatives play the role of caregivers. The advantages of such system are not limited to the controlled environment where the system runs, though. For example, when the patient is in a hospital, relatives can be informed of the state of a patient, and when s/he is at home, then a doctor may be sent reports periodically, as triggered by an agent in the third architectural level, which can be personalised to set how often the relatives or the doctors want to be updated; however, if there is an important change in the state of the patient, the lowest level sends a petition to the third level to send an alert to the relatives or the caregivers automatically. In both cases, the agents in the high level filter sensor information, adapt it to the appropriate level of detail, and finally send it to the receiver by means of e.g., a phone line, an e-mail or even a simple SMS[9] message.

5. Conclusion

Assistive technologies can support people with disabilities in ways that go far beyond the applications currently used in medicine. The power of AT is still under-recognised by physicians and its potential as an aid to patients is under-exploited. These technologies could be seen as a therapy or as a commodity. There are limits to the extent to which rehabilitation professionals can help to improve the skills of impaired people and the broader environments in which they live, and AT provide powerful means to overcome those limitations.

Although products that increase the autonomy of senior citizens are currently available in the market, often they only provide partial or superficial solutions, and address a small subset of users' needs – as mentioned in Section 1, most of them try to solve teleassistance problems, as in [15], or just offer specialised information services.

We are putting forward this proposal to provide global care for disabled and senior citizens. The tools envisaged here are applicable to support a wide range of disability levels and needs, and can be used by a wide range of users – intact healthy people and those with mild cognitive limitations, elders with moderate impairment and disability, caregivers, etc. These agent-based systems are devised to support the execution of daily life activities and of healthcare maintenance tasks – including standardised behavioural assessments useful in medical monitoring. In addition, they connect patients to the outside world, including entertainment and information, and facilitate communication with families and with the environment. Physical environments that are age-friendly can make the difference between independence and dependence for some older people, as senior citizens who can safely go outside and "walk" to a neighbour's house or to the park are less likely to suffer from isolation and depression.

Among the most important obstacles that new technologies such as software agents find in real applications in medical informatics we can mention: user expectations and acceptance, security and trust issues, lack of standards, and integration with pre-existing

[9]Short Message Service, available in mobile phones with GSM technology.

health-care systems. It can be expected that acceptance of such systems will increase in the future, as senior citizens will be more and more used to interacting with and relying on advanced technological devices. To overcome the other problems, we propose here a real integration of heterogeneous technologies to serve to disabled and senior citizen in a non-intrusive way and securing the personal information of the users, working towards an integral solution beyond existing efforts that try to solve subsets of problems.

Within this perspective, the whole range of professionals involved in health care can contribute to a more widespread awareness of the feasibility of newer ways and means of facing the problems connected to old age and disabilities. It is possible to study new ways through which scientific knowledge, the respect of autonomy, the experience of proximity with patients, the acceptance of citizenship rights, and the application of new technologies will allow the construction of a support network that can change the lives of people who are affected by such conditions. It is clear that the use of this new technological devices will help to enhance the quality of life of disabled and senior citizens and their families, and reduce institutional and societal costs in the future.

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