draft version

The SENA robotic wheelchair project

Gonzalez J., Galindo C., Blanco J.L., Muñoz A.J., Arevalo V., Fernández-Madrigal J.A.

1. Introduction

Currently, more than 45 million people in Europe suffer from some mobility limitation of different nature. Apart from labour or traffic injured people, this figure is mostly due to elder people whose number follows a worrying upwards trend. Nowadays, there are about 80 million elder people in Europe and experts predict that this number is likely to increase by over 1% per year for the next two decades.

Considering this situation, any effort aimed to facilitate mobility to physically impaired people within their daily lives is crucially relevant. A widely adopted solution to this problem is the use of *powered wheelchairs* that give impaired people considerable mobility with less physical effort than classical wheelchairs. Nevertheless, users of powered wheelchairs must still directly control the movement of the wheelchair, which may become a great nuisance when performing in certain scenarios like crowded areas, narrow corridors, or large and annoying environments.

The last years have witnessed some promising improvements in powered wheelchairs aimed to relieve users of dealing with such situations. Some powered wheelchairs include mechanisms for automatic obstacle avoidance, passing through narrow spaces, doors, etc. These mechanisms require the wheelchair to be endowed with sensors and actuators, managed and controlled by an onboard computer. In this sense, powered wheelchairs turn from user-guided vehicles into *robotic wheelchairs,* operating in a semi-autonomous manner.

Several works on this topic have been developed and a number of robotic wheelchair prototypes have been presented with marked improvements (Balcells & Abascal, 1998), (Fioretti et al., 2000), (Hoyer et al., 1995), (Levine et al., 1999), (Mazo et al., 2001), (Prassler et al., 2001). Nevertheless, the use of robotic wheelchairs is not yet widely extended due to different reasons. On the one hand the performance of most robotic wheelchairs is largely subjected to the continuous human supervision which may absorb completely her/his attention. This situation worsens when the impaired user has to perform within complex and dynamic environments, i.e., an office building. On the other hand, most users are suspicious of current robotic wheelchairs since they usually notice they are merely observers who can command the vehicle indicating what to do, but neither how to do it nor what happens in the event of a failure or abnormal behaviour. Based on these considerations, we believe that a great effort must be still done to provide physically impaired people with dependable and friendly robotic wheelchairs.

These characteristics are precisely the main requirements considered by the *Human Centered Robotics (HCR)* paradigm (Dorais et al., 1998), (Khatib, 2002), (Morioka et al.,, 2002) for the development of assistant robots. *Dependability* refers to physical safety for both people and robot, as well as to other characteristics such as operating robustness and fault tolerance. *Human-friendly interaction* implies the capability of easily commanding the robot as well as reporting execution information in a proper human-like way.

Bearing in mind all these considerations our research group has been working during the last years on the development of a robust and reliable robotic wheelchair with capabilities for high-level communication, pursuing the maximum degree of user acceptance. The result of this long-term project is the robotic wheelchair *SENA* depicted in figure 1, based on a conventional powered wheelchair endowed with a variety of sensors and devices managed by the own user's laptop.

Figure 1 The Robotic Wheelchair SENA. This vehicle is the result of several years of research in the System Engineering and Automation Department at the University of Málaga (Spain).

The main guidelines we have followed for the design are:

HCR characteristics. SENA achieves a high degree of dependability and human-friendly interaction by using a control robotic architecture called *ACHRIN* (Galindo et al., 2006). A special characteristic of ACHRIN is that the user can actively participate at all levels (from deliberation to physical actuation) which imposes a high-level communication requirements. More detail about ACHRIN is given in section 3.

User Comfort. Unfortunately, an impaired person spends almost all day on her/his wheelchair, and any additional element, i.e. sensors, may become a nuisance in her/his daily life. In our design we have paid special attention to this issue placing all components of SENA out of the user workspace. Moreover, the autonomous navigation of the wheelchair is controlled by means of her/his laptop, which can still be used for her/his work.

Modularity. Robotic devices should be designed to be easily extended and/or updated over time. For this reason, both the software and hardware of SENA use commercial and standardized products (operative systems, communication middleware, programming languages, etc.), which facilitates the upgrading and extension of its components. Specifically, software modules have been implemented under a software development system called *BABEL*, which has proven its suitability for designing good-quality, modular and distributed robotic applications (Babel, 2006), (Fernández & Gonzalez, 2002).

In the following sections, the components of SENA (hardware and software) are described in detail. Then some real experiences of the usage of SENA are presented demonstrating its suitability to perform within a variety of situations. Finally the conclusion of our work and the future lines of research in the field of assistant robotics are outlined.

2. The Hardware of SENA

The robotic wheelchair SENA (see figure 1) is built upon a commercial powered wheelchair (Sunrise Powertec F40) on which several sensors and devices have been mounted and coordinated to reliably perform high-level tasks in indoor environments.

The hardware components of SENA are depicted in the scheme of figure 2. It is important to remark that the original wheelchair has undergone minimal modifications: two encoders have been connected to the motors' axis to estimate the wheelchair odometry and the original battery's voltmeter, as well as the joystick line, have been bypassed to a microcontroller placed bellow the batteries' cage. A switch which can be operated manually or through the computer by a verbal command, selects the input of the motor system to be either the joystick signal or the output of the computer control. This allows the user to turn off the autonomous navigation of SENA and begin a manually guidance.

The SENA microcontroller serves as an interface to all sensors and devices and implements the low-level motion control of the vehicle. In turn, high-level algorithms like mapping, self-localization, voice speech/recognition, etc., are executed by a laptop which is connected to the vehicle microcontroller via USB (see figure 2)

Next, the different sensors of SENA are deeper described.

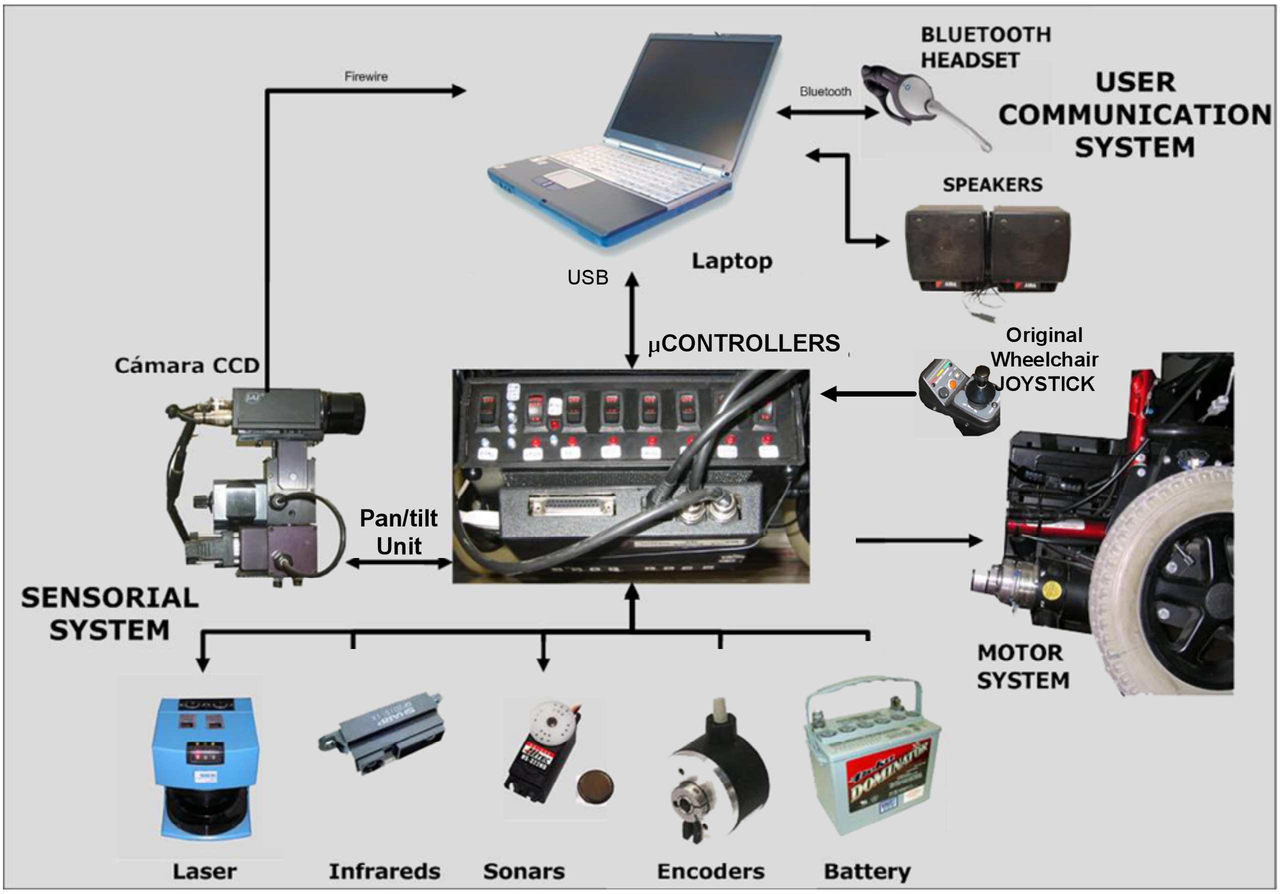


Figure 2. Scheme of the hardware of SENA. Low-level control of sensors and motors is carried out by a microcontroller that provides a high-level interface to the software running in the laptop. Our design provides high flexibility, since the user can be working on her/his personal computer at the same time it takes care of commanding the wheelchair.

SENA is endowed with the following sensory system:

- A *CCD camera* mounted on a pan-tilt unit serves to localize SENA. In contrast to the rest of sensors commented further on, the CCD camera is placed at a high position, approximately 1.70 m., from where perceived elements of the environment are nearly static (walls, windows, furniture, etc.).
- A *180º radial laser scanner* mounted on a retractable mechanism is placed in front of the wheelchair, between the user legs for avoiding any nuisance to her/him (see figure 3). The use of this kind of sensory devices is widely extended in mobile robots since they exhibit a high precision and quick sampling of the surroundings. In our application, the laser scanner is employed to detect obstacles, for environment map building, and self-localization (Blanco et al, 2006a,b), (Reina & Gonzalez, 2000).

Figure 3. The radial laser scanner provides valuable information from the environment for obstacle avoidance, self-localization, mapping, etc. Its placement in front of the wheelchair permits it to scan with no dead angles and without obstructing the user.

- A *ring of thirteen infrared sensors* are placed around SENA to detect close obstacles when the wheelchair is maneuvering (see figure 4). Infrared are small and cheap sensors that provide an operational range between 10 to 70 cm., enabling the wheelchair to securely approach objects and furniture. Two of them are located underside the wheelchair to check for portholes, curbs, stairwells, etc. Another two infrared sensors are located in the backside to detect possible obstacles when SENA moves backwards.
- *Two ultrasonic rotating sensors* are also located in front of SENA. Each one is mounted on a servo which enables it to scan a 180º field of view. Ultrasonic sensors present lower precision than the laser scanner and its scanning period is higher, however they are complementary since sonars survey at a different height and can detect transparent and narrow objects which may not be properly captured by laser sensors.

As commented, the selection and placement of SENA’s sensors are aimed to provide fault tolerance, robust operation. Some critical tasks like obstacle detection or localization make use of the redundant and complementary information provided by them.

The vehicle accounts for two small speakers and a bluetooth headset for communication with the user through a commercial speech generation and voice recognition software. This verbal communication, which is supported by a particular symbolic world model (Fernández-Madrigal et al, 2004) described in the next section, provides a high-level human-like communication (please refer to (Fernández-Madrigal & Gonzalez, 2001) for further explanation).

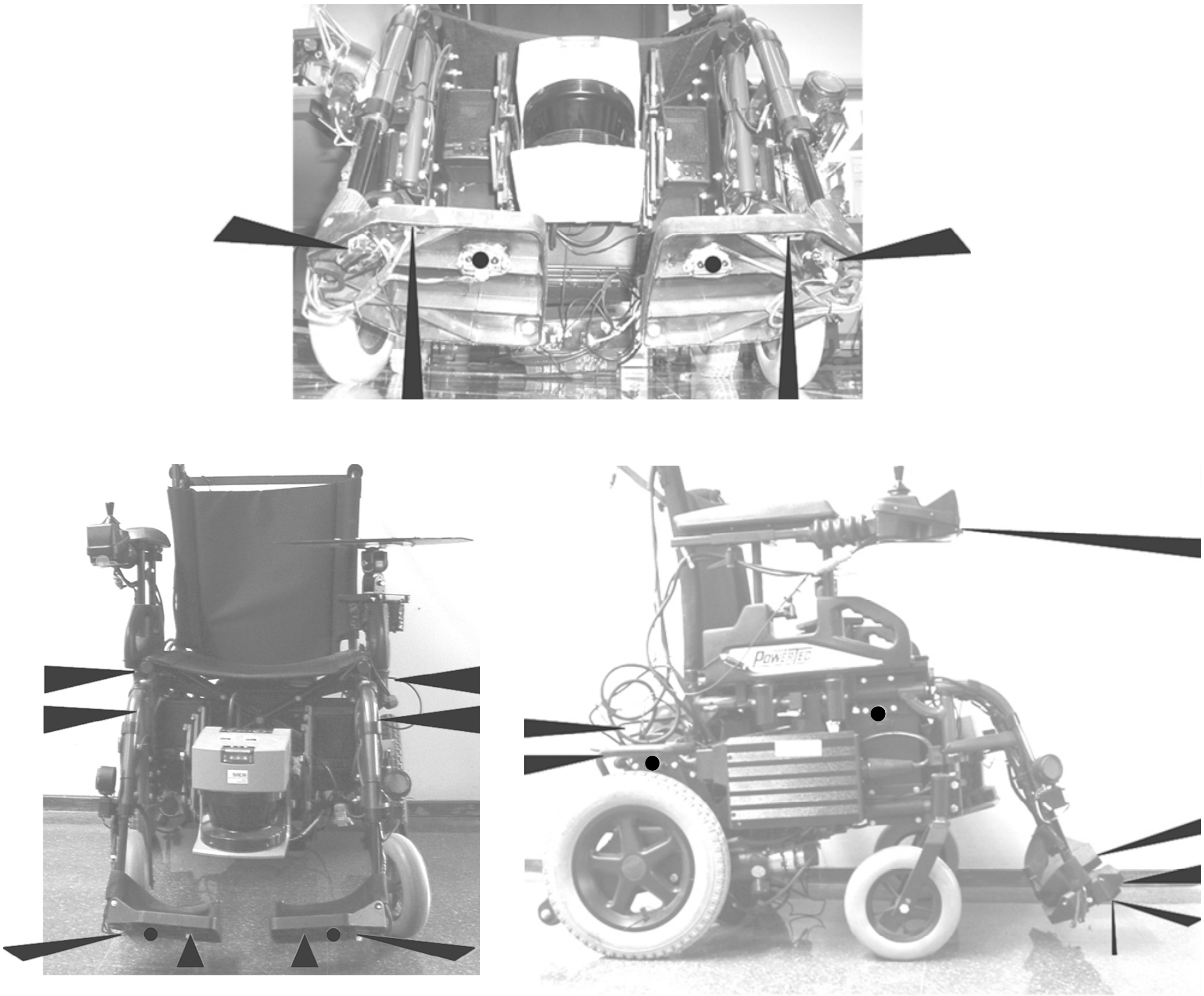


Figure 4. Portion of space scanned by the ring of infrared sensors. They are placed at positions that complement the space sampled by the radial laser scanner.

Finally it should be noticed that every hardware component considered for SENA provides standard connections that permits us to easily upgrade, extend, or modify the current configuration of the wheelchair with newer and powerful devices when needed.

In the following the software architecture that intelligently manages the wheelchair is detailed.

3. The Software Architecture of SENA

Apart from a complete set of sensors capable of providing environmental information, a proper software architecture is also needed to manage such information and to devise the most convenient strategy when dealing within human environments.

In general, the robotic presence in our daily life is still quite limited since the full autonomous performance of robotic vehicles within real scenarios is not completely possible yet.

Our particular solution to overcome this lack of autonomy is a software architecture that includes the wheelchair user as an extra component who can help the system when needed. That is, assuming that the wheelchair user has enough cognitive abilities, for example to correct the position of the vehicle, and physical abilities to manipulate objects, i.e. open a door or call an elevator, her/his skills may improve or extend the robotic system.

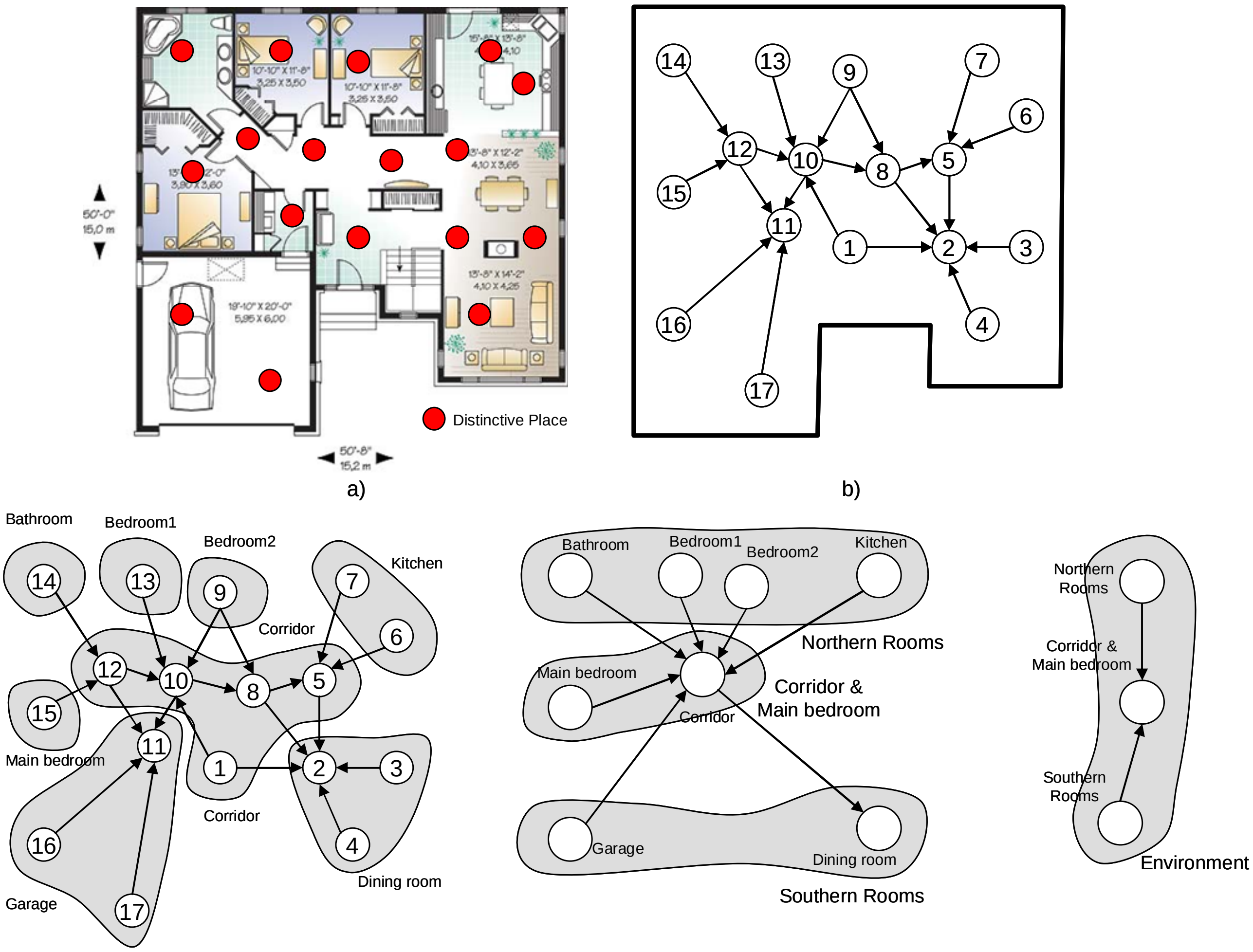
This particular relation imposes a close human-robot interaction in which high-level communication takes an special significance since people that can extend the robot autonomy (typically the user or a person in the surroundings) do prefer to communicate and to interact with machines in the same manner they do with other people. Thus, for example when wheelchair sensors detect a closed door, the robot should be allowed to ask for help through an understandable way for humans, i.e. "please, open the door which is in front of us". Notice that in our solution, the human help is required only when it is strongly needed, without continuously annoying the user who must feel the wheelchair performance as almost completely autonomous.

In this sense, we have designed and implemented a software architecture that permits the human to participate in the wheelchair operation. This architecture, called *ACHRIN* -Architecture for Cognitive Human-Robot Integration- (Galindo et al., 2006), integrates humans into the robotic system by extending the system abilities through skills either not supported by the robot (i.e. take and elevator) or supported by the robot but in a different and (maybe) more secure manner (i.e. maneuvering in a complex situation).

Although the human participation into the robot operation is a widely studied field (Goetz & Kiesler, 2002), (Tahboub, 2001), (Fong & Thorpe, 2002), (Fong et al., 2001), (Scholtz, 2003), our solution takes a further step by providing a special human-robot integration that we called *cognitive integration* (Fernández-Madrigal et al., 2004) which permits high-level communication between the vehicle and humans by means of *abstraction*. Abstraction is a mechanism widely used by humans (Hirtle & Jonides, 1985) (Kuipers, 2000), (Harnand, 1987), (Kuipers, 1983) that serves to reduce the amount of information considered for coping with a complex and high-detailed world: concepts are grouped into more general ones and these are considered new concepts that can be abstracted again. The result is a hierarchy of abstraction or a hierarchy of concepts that ends when all information is modelled by a single universal concept (see figure 5). Enabling the robotic wheelchair to symbolically manage spatial information through abstraction, a direct interface between the vehicle and the map-in-the-head carried by the human (the cognitive map[1]) (Kuipers, 1983) can be established.

---

[1] The cognitive map can be defined as the human internal representation of large-scale space.



a)

b)

c)

Figure 5 An example of a hierarchy of abstraction. (a) A schematic plan of an environment. Distinctive places for robot navigation are marked with circles. (b) Ground level: topological map of distinctive places. (c-d) Upper levels of the hierarchy. Gray-shaded regions contain the set of nodes which are abstracted to a common spatial concept. Linguistic labels can be attached to spatial concepts to improve human-robot communication.

ACHRIN (see figure 6) is a layered robotic architecture (Arkin, 1998) that enables humans to offer extended functionality to all levels, from deliberative to low control level. The main features provided by ACHRIN are:

-*Human and vehicle can communicate in a human-like manner*. Through cognitive integration the vehicle can share part of the human symbolic world model, and thus, SENA and the user can univocally refer to the same world concepts: objects, places, etc. using their names in a common language (Fernández-Madrigal et al., 2004). Such a cognitive integration is achieved through the use of a hierarchical and symbolic model.

-*Humans can extend the vehicle capabilities with new skills*. These skills may range from complicate low-level motions to high-level decision-makings, for instance to open a door, to warn the system about risky situations undetectable by the wheelchair's sensors, to plan the most convenient path to arrive a destination, etc. It is remarkable that not only the wheelchair user can extend the wheelchair skills but also any person in the surroundings.

-*Humans can improve some robot skills*. Humans can perform the actions initially assigned to the vehicle in different and sometimes, more dependable ways. Also the user or any person of the surroundings can complete actions that occasionally have failed. For example, the wheelchair user can recover the vehicle from a navigation failure by manually guiding it to a well known location where the machine could continue navigating autonomously.

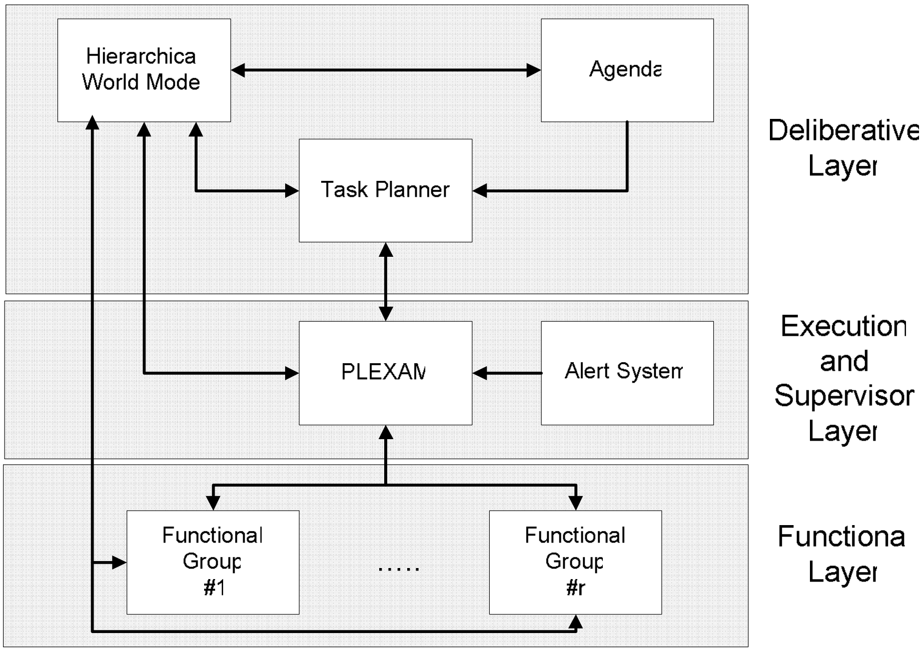


Figure 6. A general view of ACHRIN. Broadly, it can be considered as a hybrid robotic architecture. However, it does not present the typical hierarchical arrangement since the shared world model is accessed by most components of the architecture (an exception is the Alert System).

Briefly, the functionality of each layer of ACHRIN is commented:

-*Deliberative layer*. This layer maintains a symbolic representation of the world and produces plans to achieve robot goals (Galindo et al., 2004b). The cognitive integration between the user and the assistant robot is attained through a shared hierarchical world model, which permits among other features human-vehicle interactive path planning (Galindo et al., 2004a).

-*Executive and Control layer*. It supervises the execution of plans managing the information collected from the functional layer and the vehicle's sensors. It tunes the behavior of the wheelchair with respect to the dangerousness of risky situations detected by its sensors, i.e., collision.

-*Functional layer*. It is composed of a number of modules which physically perform actions for navigation, manipulation, communication, etc. These modules are organized into functional groups according to their functionality, possibly containing different mechanisms to accomplish the same action. For example, the wheelchair can traverse two spatial points either reactively, following a pre-recorde path or guided by the user.

As commented before, ACHRIN enables humans to interact at all levels of the architecture in order to extend and/or to improve the functionality given by any module. Modules of ACHRIN take into account human capabilities through the so called *skill units*. Each module of the architecture can be composed of a variety of skill units that execute a particular ability or action, like producing a plan, checking for a risky situation, moving between two locations, etc. Such actions can be carried out either by the human or by the vehicle, executing the corresponding skill unit. In the case of the robot, skill units are implemented using software algorithms, while in the case of the human, they enable the human to perform actions and communicate to the vehicle through appropriate interfaces, i.e. *via voice*. (please refer to (Galindo et al., 2006) for a deep explanation).

4. Experiences with SENA

From its beginnings, the robotic wheelchair SENA has aroused the curiosity of students, colleagues, visitors, and media. Several demonstrations and appearances in television (some of them in live programs) have been conducted in the last years with a high degree of success and revealing the utility of our prototype (see figure 7).

Figure 7. Some demonstrations conducted with SENA. Our wheelchair has been tested in a variety of situations and with different people (some of them on live TV programs).

In the following some interesting scenarios and features that reveal the potentiality of the SENA prototype are commented. Low level navigational abilities employed in SENA are not covered here, but can be found elsewhere (Blanco et al., 2006a), (Blanco et al., 2006b).

4.1 Improving/extending robot abilities

The scenario described in this section shows the necessity of the human-vehicle integration we propose. A user performing within a typical office environment, sends a document to a remote printer and wants to go to the room where the printer is to get her/his copy.

Figure 8. SENA-human integration. When performing within a complex and dynamic scenario, the human help can be required to solve complex situations (b,d). In this sense, SENA and user cooperate: the vehicle provides mobility to the user while she/he manually overcomes the wheelchair limitations.

This simple example may exhibit complex inconveniences like, for example, if the door of the room is closed or the navigational system of SENA fails due to the narrowness of the environment. For the first problem, the human help is unavoidable since SENA is not able to open doors. In this case the planning system of ACHRIN realizes the necessity of the human participation in the plan. For the second problem, present in any real application, the user may detect the automatic navigation failure, and notify to the control of SENA which requests the user to solve manually this situation. Figure 8 shows some snapshots of this scenario. The full movie can be downloaded at http://www.isa.uma.es/research/sena

4.2 Interactive path planning

Regarding human-vehicle communication, another relevant feature of SENA is its ability to provide different possible solutions when planning a path. We call this: “interactive planning”, since the user participates in the planning process accepting or rejecting the proposed solutions (Galindo et al., 2004a). This faculty is of a great relevance for a robotic system intended to coexist with people since automatic planners can provide the best solution to attain a goal based on fixed cost functions, i.e. the distance to be travelled, or previous experiences, but without satisfying the user requirements. That is, we, humans, may have different subjective criteria impossible to be captured by any software algorithm. In our experiences on interactive path planning, the user may prefer the worse path to arrive a destination for a variety of reasons: “the shortest one is crowded at this moment”, “I want to stroll”, “I want to pass near the Mary office to say hello”, etc. A video showing our interactive planning approach can be downloaded at http://www.isa.uma.es/research/sena

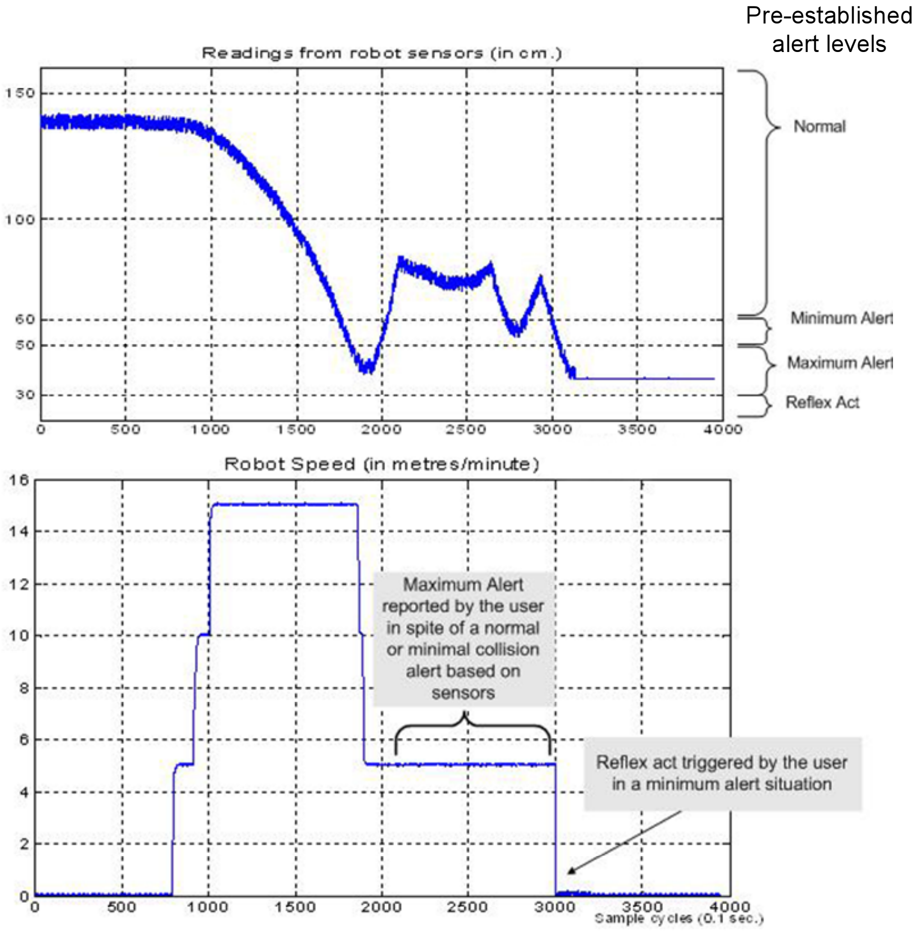
4.3 Alerts and reflexes management

Finally, it is also remarkable the way in which SENA reacts to external stimuli through alerts and reflexes (the most critical alert). Within the control architecture, the Alert System module checks for unexpected dangerous situations warning the user about, for example, collisions or low-battery situations. In addition, the wheelchair user is also integrated into the Alert System through reporting risky situations (possible not detected by the vehicle sensors) using verbal commands like "there is a collision risk" or "the battery level is low".

The integration of the human into the alert system of ACHRIN enhances the reliable performance of the robot, since she/he can report danger situations not detected by robot sensors. Besides, the human can also predict future risky situation based on her/his knowledge about the environment, and thus, for example, she/he can notice about a collision risk when the vehicle is close to enter a room which is probably crowded.

The user plays a dominant role in the Alert System module since alerts reported by her/him are prioritized. Thus, the user can ignore, for instance, a minimal alert of collision based on the readings of a laser rangefinder sensor if she/he is sure there is not a really danger, i.e. they are passing through a door. This feature permits humans to modulate the behavior of SENA to her/his wills, i.e. when the user, intentionally, wants to closely approach a wall to read a sign.

Figure 9 shows the evolution of the collision alerts in part of one of our experiences in which the user overrides the alert signals based on sensor readings to adequate the SENA navigation to her/his feelings. For instance, from cycle #2000, where the system reports a minimum alert based on sensor measurements, the user maintains the maximum alert in order to set the SENA speed to a low value.


Pre-established alert levels

Maximum Alert reported by the user in spite of a normal or minimal collision alert based on sensors

Reflex act triggered by the user in a minimum alert situation

Figure 9. Evolution of collision alerts over time in a real experience (1 sample cycle=0.1 sec.). Top: Minimum distance measured by SENA's sensors to the closest obstacle. Bottom: Speed of SENA during a part of one of our experiences. Notice how the user can override the alert system as around cycle #2000.

5. Conclusions and future work

In this chapter we have presented the robotic wheelchair SENA, a long-term project aimed to facilitate the mobility to impaired and elderly people. After several years of research, our group has developed a dependable and reliable prototype that provides people the possibility to perform almost autonomously within complex and daily environments.

Although several goals have been achieved in our work, the future of our research goes on the line of improving our hardware/software design as well as to make our robotic wheelchair accessible to the common public.

Finally, authors would thank the inestimable effort and dedication of the large number of researchers, master, and PhD students who have worked on the development of SENA.

6. References

Arkin R.C. (1998). *Behavior-Based Robotics*. The MIT Press Cambridge.

BABEL Development System homepage: http://www.isa.uma.es/investig/babel/investig.htm (Acceded on Nov, 2006)

Balcells A. C. and Abascal J., (1998) *TetraNauta: A Wheelchair Controller for Users with Very Severe Mobility Restrictions*, 3rd European Conf. on Tech. for Inclusive Design and Equality, Helsinki, Finland

Blanco J.L., Fernández-Madrigal J.A., Gonzalez J. (2006a). *An Entropy-Based Measurement of Certainty in Rao-Blackwellized Particle Filter Mapping*. Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Beijing (China), Sep 9-15, 2006.

Blanco J.L., Gonzalez J,, and Fernández-Madrigal J.A. (2006b), *The Trajectory Parameter Space (TP-Space): A New Space Representation for Non-Holonomic Mobile Robot Reactive Navigation*. Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Beijing (China), Sep 9-15, 2006.

Dorais G., Bonasso R.P., Kortenkamp D., Pell B., and D. Schreckenghost (1998). *Adjustable Autonomy for Human-Centered Autonomous Systems on Mars*. Proc. of the First International Conference of the Mars Society, pp. 397—420.

Fernández-Madrigal J.A., and González J. (2002) *A Visual Tool for Robot Programming*, 15th IFAC World Congress on Automatic Control, Barcelona, Spain.

Fernández-Madrigal J.A., and Gonzalez J. (2001), *Multi-Hierarchical Representation of Large-Scale Space*. Kluwer Academic Publishers.

Fernández-Madrigal J.A., C. Galindo and J. Gonzalez (2004). *Assistive Navigation using a Hierarchical Model of the Environment*. Integrated Computer-Aided Engineering Vol. 11, No.4, pp. 309-322.

Fioretti S., Leo T., and Longhi S. (2000). *A Navigation System for Increasing the Autonomy and the Security of Powered Wheelchairs*. IEEE Trans. on Rehabilitation. Engineering, vol. 8.

Fong T.W., and Thorpe C. (2002). *Robot as Partner: Vehicle Teleoperation with Collaborative Control*. In Proceedings of the NRL Workshop on Multi-Robot Systems, pp. 195-202.

Fong T.W., Thorpe C., and Baur C. (2001). *Collaboration, Dialogue, and Human-Robot Interaction*. 10th International Symposium of Robotics Research, Lorne, Victoria, Australia, pp. 255 – 270.

Galindo C., Gonzalez J., and Fernández-Madrigal J.A (2004a). *Interactive Task Planning in Assistant Robotics*. In Proc. 5th Symposium on Intelligent Autonomous Vehicles, Lisbon.

Galindo C., Fernández-Madrigal J.A., and Gonzalez J. (2004b). *Hierarchical Task Planning through World Abstraction*. IEEE Transaction on Robotics, vol. 20, No.4, pp. 667-690.

Galindo C., Gonzalez J., and Fernández-Madrigal J.A. (2006) *A Control Architecture for Human-Robot Integration: Application to a Robotic Wheelchair*. IEEE Transaction on Systems, Man, and Cybernetics--Part B, vol. 36, No. 5, pp. 1053-1067.

Goetz J. and Kiesler S. (2002). *Cooperation with a robotic assistant*. In CHI '02: Extended abstracts on Human factors in computing systems, Minnesota, USA.

S. Harnand (1987). *Psychological and Cognitive Aspects of Categorical Perception: A Critical Overview*, Harnand S. (ed.), New York, Cambridge University Press, Chapter 1.

Hirtle S.C. and Jonides J. (1985), *Evidence of Hierarchies in Cognitive Maps*. Memory and Cognition, Vol. 13, No.3, pp. 208-217.

Hoyer H., Hoelper R., Borgolte U., Bühler C., Heck H., Humann W., Craig I., Valleggi R., Sabatini A.M. (1995), *The OMNI Wheelchair with High Manoeuvrability and Navigational Intelligence*, in Rehabilitation Technology, Proc. of the 2nd TIDE Congress, Brussels, IOS Press.

Khatib O (2002). *Human-Centered Robotics and Haptic Interaction: From Assistance to Surgery, the Emerging Applications*. Third Int. Workshop on Robot Motion and Control.

Kuipers B.J. (1983), *The Cognitive Map: Could it Have Been Any Other Way? Spatial Orientation: Theory, Research, and Applications*. Picks H.L. and Acredolo L.P and New York, Plenum Press.

Kuipers B.J. (2000), *The Spatial Semantic Hierarchy*. Artificial Intelligence, Vol. 119, pp. 191-233.

Levine S. P., Bell D. A., Jaros L. A, Simpson R. C., Koren Y., and Borenstein J. (1999). *The NavChair assistive wheelchair navigation system* IEEE Trans. on Rehabilitation Engineering, vol. 7.

Mazo M., and the Research Group of the SIAMO Project (2001). *An Integral System for Assisted Mobility*. IEEE Robotics and Automation Magazine, vol 7.

Morioka K., Lee J-H, and Hashimoto H. (2002) *Human Centered Robotics in Intelligent Space*. In Proceedings of ICRA 2002, DC.

Prassler E., Scholz J., and Fiorini P. (2001). *A Robotic Wheelchair for Crowded Public Environments*. IEEE Robotics and Automation Magazine, vol. 7.

Reina A., Gonzalez J. (2000), *A Two-Stage Mobile Robot Localization Method by Overlapping Segment-based Maps*. Robotics and Autonomous Systems. Elsevier Science. Vol. 31.

Scholtz J. (2003). *Theory and evaluation of human-robot interaction*. 36th International Conference on System Sciences, Hawai, pp. 1-10.

Tahboub K.A. (2001). *Semi-Autonomous Reactive Control Architecture*. Intelligent Robotics Systems, vol. 32 No. 4, pp. 445-459.