Personal autonomy rehabilitation in home environments by portable assistive robot

Alberto Jardón, Juan G. Victores, Santiago Martínez, Antonio Giménez, Carlos Balaguer
IEEE members

***Abstract*—More and more disabled and elderly people with mobility problems want to live autonomously in their home environment. They are motivated to use robotic aids to perform tasks by themselves, avoiding permanent nurse or family assistant supervision. They must find means to rehabilitate their abilities for performing DLA's[1] such as eating, shaving, or drinking. These means may be provided by robotic aids that incorporate possibilities and methods to accomplish common tasks, aiding the user in recovering partial or complete autonomy. Results are highly conditioned by the system's usability and potential. The developed portable assistive robot ASIBOT helps users perform most of these tasks in common living environments. Minimum adaptations are needed to provide the robot with mobility throughout the environment. The robot can autonomously climb from one surface to another, fixing itself to the best place to perform each task. When the robot is attached to its wheelchair, it can move along with it as a bundle.**

This paper presents the work performed with the ASIBOT in the area of rehabilitation robotics. First, a brief description of the ASIBOT system is given. A description of tests that have been performed with the robot and several impaired users is given in Section III. Insight on how these experiences have influenced our research efforts, especially in home environments, is also included. A description of the test-bed that has been developed to continue research on performing DLA's using robotic aids, a kitchen environment, is given in Section IV. Relevant conclusions are included in final Section V.

***Index Terms*—Homecare, Rehabilitation robotics, Clinical trials, Portable robots, Climbing robots, Inclusive technologies.**

I. Introduction

MOST human manipulation tasks require the use of the upper limbs. Due to this, any deficiency in them causes a loss of dexterity and less performance in manipulation. Among disabled people, people with difficulties using arms and hands are a very representative group. These difficulties affect common DLA's involving manipulation such as moving objects, using tools or utensils, manipulating small objects, washing, getting dressed, opening and closing doors and drawers, turning switches on and off, eating, or drinking.

Technical aids are very useful for psychological rehabilitation and personal motivation, which may be achieved by means of training to perform simple activities with minimal or no external help. Assistive robots have the ability to help people and are capable of providing personalized assistance, individually or in teams [1]. They act as specialized people in helping, supporting, and monitoring people with needs, giving them daily independence [2], [3]. During these past 15 years, robotic technology has been evolving to become more flexible and adaptable towards human rehabilitation technique. Assistive robots are made to help people, to support disabled and elderly people with special needs, inside their own homes and everyday environment.

Traditional rehabilitation robotics technology has been focused on three main development concepts: static systems that operate in structured environments, wheelchair mounted robotics systems, and mobile manipulator companions capable of following the user for personal and care applications.

The first type of robotic system is very useful for people who need assistance in a reduced part of a living environment and for fixed set of applications, such as eating or drinking. The Handy 1 Robot Arm [4] is an excellent example of a static robot system. It is a low-cost solution for personal care and assistance. Over 400 units have been placed in the market to date. Nevertheless, static robot systems have one great limitation: changing their location can be difficult and may some times be near impossible. Using the robot for shaving in a bathroom and eating in another floor could mean having to carry the robot up and down the stairs and fixing and unfixing it manually very frequently. Another inconvenience of static robots is that they intrinsically have limited maneuverability and dexterity due to their static base positioning.

Another type of rehabilitation robots is the wheelchair mounted type. The current market leader of this type of robot is the MANUS system [5]. More than 60 units have been placed to date. The arm is permanently fixed to either the left or right-hand side of the wheelchair. This fixed asymmetry may be of inconvenience for the execution of certain tasks. Additionally, the "bundled" concept implementation may produce mobility problems through doors and stairs. Moreover, the cost of this kind of systems is usually very high.

The third concept suggests a mobile manipulator that follows the user's wheelchair in a structured environment. This concept has disadvantages similar to those of the previous ones. Mobility around a domestic environment is not always ideal due to steps or obstacles. Nevertheless, this concept introduces one new great advantage: the robot has the ability to move around the environment, with independence from the wheelchair or the user. A popular example of this kind of robotic system is the KARES II mobile manipulator [6].

The assistive robot ASIBOT (Figure 1) has been developed by the Robotics Lab research group at UC3M and has been endowed with a series of advantageous characteristics,

Alberto Jardón, Juan G. Victores, Santiago Martínez and Carlos Balaguer are members of Robotics Lab research group within the Department of Systems Engineering and Automation, Universidad Carlos III de Madrid (UC3M), (ajardon, scasa, jcgvicto, balaguer)@ing.uc3m.es

Antonio Giménez is member of the Department of Mechanical Engineering, Universidad de Almería, Spain, agimfer@ual.es

[1]DLA's: Daily Life Activities

unprecedented in other assistive robots. It introduces several useful and unique features:

- Light-weight symmetrical structure for climbing.
- Full on-board robot control and communication systems.
- Unlimited workspace through 24V climbing connectors.
- Tool exchange system for grippers, utensils, sponge, etc.
- Portable and friendly HMI adapted to different levels of user capabilities and preferences.
- Control architecture for integration with environment.

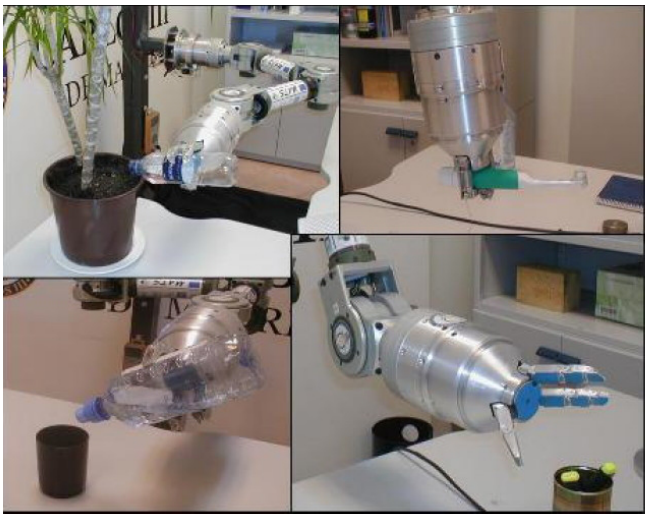


Fig. 1. The assistive robot ASIBOT is portable and has multiple abilities

This paper is composed by a technical description of the assistive robot ASIBOT, and details about experimental results in real domestic environments. Procedures and results of tests in hospital and real domestic environments (a bathroom, and a kitchen) will be presented. These trials are not just test simulations or laboratory experiments; they represent a significant advance in assistive robotic application science working with real patients. Tests are focused on determining the end user acceptability using the robot's unique features and interfaces, therefore differing from clinical trials performed with Raptor or MANUS bundled-type systems, which have been evaluated in tests involving groups composed by a similar amount of potential end users [7], [8] by different institutions.

II. ASIBOT PORTABLE & PERSONAL ROBOT

We have managed to introduce climbing and manipulator arm technology into a new robot design with the purpose of assisting disabled people. The ASIBOT assistive robot extends human capabilities providing them a way to recover partial autonomy, performing a large variety of domestic operations: house-keeping, self-care, entertainment... It is actually designed to fit into any environment. The robot can move accurately and reliably between rooms and up or down stairs, and can transfer from the wheelchair to floor, ceiling or wall. This degree of flexibility has significant implications for personal assistance in domestic environments.

A. ASIBOT portable design and climbing abilities

ASIBOT is a portable five degree of freedom manipulator arm (see Figure 2). Its design is symmetrical, and is composed by two main parts: the articulated arm structure, and the two tips. The articulated body contains two links inside of which all of the electronic equipment and the control unit of the arm are embedded. Each one of the two tips is able to perform two very different functionalities. A tip can connect to a Docking Station (DS, a climbing connector that provides 24V power supply) and act as a base for the robot, or be free to perform manipulation tasks. It is important to note that the robot arm's symmetry allows properties such as the kinematic chain description and therefore maneuverability to be (in theory and in practice) independent from which tip is being used as the robot base.

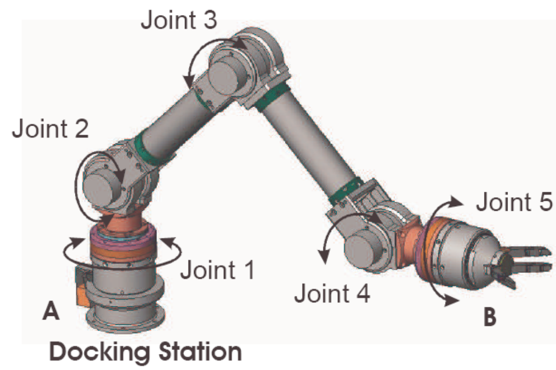


Fig. 2. ASIBOT 3D representation: DS on one side, gripper on opposite

The portability of ASIBOT is achieved due to its light weight. As a 12 kg manipulator with a 1.3 m reach, its weight / length ratio is extremely low compared to other manipulator arms, even without considering all of its control systems are on-board. Its payload at tip ranges approximately 2 kg. Communication with the robot is performed wirelessly, through a 802.11b secured local area network.

As previously mentioned, the ASIBOT robot can climb from one location to another by attaching its tips to the environment. This moving concept is similar to the CMU's SM2 robot, which uses grippers to attach itself to the space structure [9]. It is also similar to the UC3M ROMA robot developed earlier by some of the authors of this article [10]. ASIBOT's unique feature, however, is its ability to attach itself to the environment (or wheelchair) by using especially designed low-cost DS's, which allow it to maintain its manipulation skills. DS's are placed to supply power to the robot allowing it to move and work throughout the entire environment. When a DS is incorporated to a wheelchair where batteries are available, 24V power supply may be provided from a direct connection from the batteries to the DS. This concept has been implemented on the wheelchair seen in Figure 3. This way, even outdoor tasks can be achieved while battery autonomy lasts.

Indoors, DS may be placed on walls, ceilings, or be furniture-mounted. Walls and ceilings are actually recommended places for DS, since in most cases these spaces

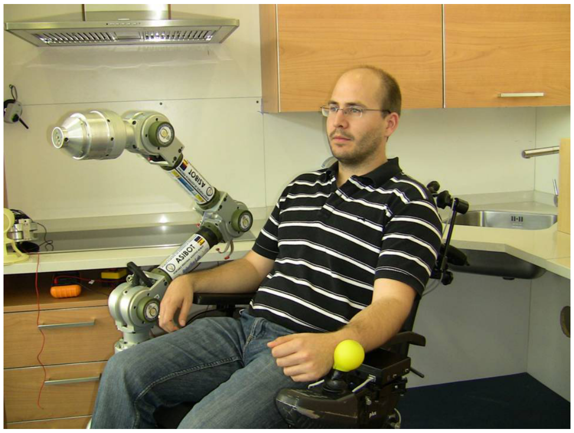


Fig. 3. ASIBOT assistive robot fixed on a wheelchair's installed DS

are underutilized. This way, the floor remains free, letting wheelchair users move easily around the environment. Due to the robot's light weight, usually no special modifications are needed for fixing DS's on walls or furniture.

As mentioned in Section I, the majority of the mobile assistive robots that have been developed navigate in 2D indoor environments. They lack degrees of freedom and are mounted on the user's wheelchair, like MANUS, or they are fixed to rails as RAID [11], which occupies a lot of floor surface. The ASIBOT robot can virtually increase its degrees of freedom by moving in 3D space, from DS to DS. Figure 4 shows an ASIBOT climbing sequence, where the robot performs transitions from one surface to another, passing through being attached to three different perpendicular planes [12]. This climbing ability is achieved through the successive fixation and release of tips at DS's. Software permanently assures that of at least one of the tips of the robot is docked at a time.

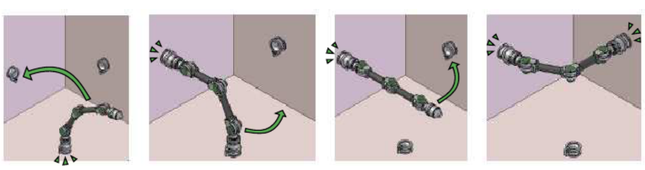


Fig. 4. ASIBOT robot 3D climbing ability: moving sequence

B. *ASIBOT end-effectors*

Each tip of the robot is in fact a special male conical connector. DS's, on the other hand, are actually female static conical connectors, and are provided with a bayonet locking mechanism (seen on Figure 5) that rigidly fixes the robot.

Inside each male connector lies a gripper that is able to manipulate objects. It is in fact a three-fingered hand with 7 phalanges per finger. Fingers are hidden at docking position (initial state of the sequence represented in Figure 6) and can be released (complete sequence represented in the figure) at will. Tendons drive all of the joints together and allow shape adaptation for grasping [13], [14]. They are activated by a

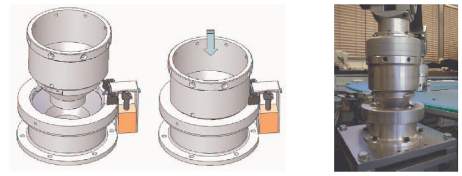


Fig. 5. ASIBOT docking mechanism, tip inserted and locked into a DS

single internal motor controlled by its corresponding CAN node. Despite this underactuated and complex design, reduced grasping capabilities are provided, capable of grasping many domestic objects within the robot's 2 kg payload limitation.

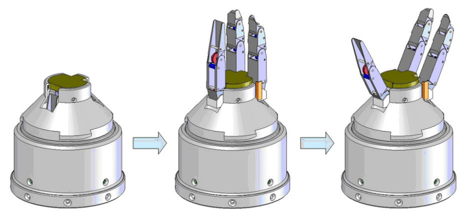


Fig. 6. ASIBOT gripper, sequence from hidden to released state

The end-effectors of the ASIBOT are currently under re-design in order to find a more economical and robust solution. Human-like manipulation strategies implemented on-board would be very complex to achieve due to mechanical and control issues needed for autonomous or partially assisted grasp planning and execution. As well as common challenges for robotic hand design, an ASIBOT gripper must always have to additionally achieve mechanical fixing in the DS, and connect electrical contacts for power supply. This is to comply with critical restrictions present in any type of climbing robot: gripping, and providing power.

However, robotic restrictions and design issues are not important from point of view of end-users. Practical alternative solutions must be provided. User's demands are related to usability and the total price of the system. As an alternative, an extensive set of low cost tools has been designed and manufactured. Rapid prototyping techniques have been used to adapt common household environment related tools. These adaptations have been tested by potential end-users, and are fully compatible with the existing ASIBOT gripper in its hidden position. Figure 7 shows some of these adapted tools: spoon and cup adaptations for eating and drinking assistance, toothbrush and makeup adaptations for bathroom assistance. All of these adaptations are low-cost and functional.

C. *ASIBOT Human-Machine Interface (HMI) and user profile*

A fundamental aspect of ASIBOT is its portability. Due to its light weight, it has the capability to be moved by a single person without aid, and be carried from one place to another easily. As a climbing robot, all hardware and electronics are on-board to avoid cumbersome "umbilical" wires. One more fundamental element exists to promote and maintain portability: ASIBOT's HMI is also portable.

Fig. 7. ASIBOT can use a variety of tools adapted to user's needs

The control system given to the user is based on a multi-modal interface that has been developed and compiled to work on a PDA to provide an assisted tele-operation system [15]. The provided multi-modal interfaces for controlling the robot include: tactile screen, using a pointer or a finger, using a scanning system and a button to select options, attaching a joystick, and a voice recognition system. It is also possible to combine some of these control modes in order to adapt the interface as much as possible to the specific needs of different users. The ASIBOT HMI can be configured to use external joysticks as user activity transducers (Figure 8, all except top right), or to use the wheelchair's driving joystick in order to reduce the number of used control devices.

Fig. 8. Several of ASIBOT's multi-modal HMI devices

This user-oriented HMI is designed to control the robot in two different modes: pre-programmed movement mode, and user-controlled robot movement mode. Using the former control mode, only objects (i.e. dishes) placed precisely at pre-defined positions can be manipulated; whereas, in the latter mode, control is completely delegated to the user, and movements in the entire workspace of the robot arm are allowed (control sub-modes include Joint space and Cartesian space). The screenshot of the HMI display unit presented at Figure 8 (top right) corresponds to the pre-programmed movement control mode. The user-controlled robot movement control mode is available through most of the presented multi-modal HMI devices. The user-controlled robot movement control mode allows compliance with uncertainty, but task execution becomes tedious for the non-expert. Executing pre-programmed tasks is much faster, yet such systems cannot meet with all of the users' requirements. Additionally, the effort required to program tasks has been criticized. A need has been marked for a non technically-oriented person to be provided with easy tools for performing and programming tasks. The conflicting constraints are to maximize flexibility while minimizing the amount of time it takes to perform a task. Special attention is paid to the variety and diversity of possible users and interaction devices, as overall system performance is HMI dependant, and usability plays a fundamental role in HMI design. Potential users are very limited in the ways in which they can interact with devices.

Cervical (neck) injuries usually result in full or partial tetraplegia (quadraplegia). Depending on the exact location of the injury, a spinal cord injured person at cervical level may retain some amount of function (as detailed below), but is otherwise completely paralyzed. Figure 9 illustrates the specific affected spinal cord regions. The scale referred to in this figure and throughout the rest the paper is the following.

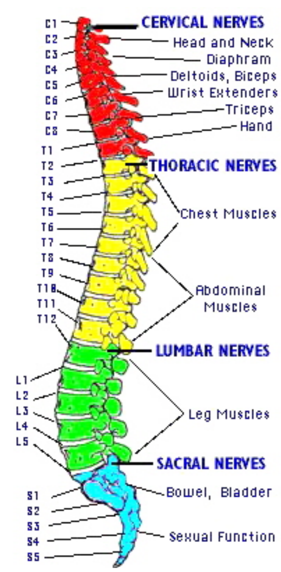


Fig. 9. The location of injury effects is important when predicting which parts of the body might be affected by paralysis and loss of function

- C3 vertebrae and above: Typical loss of diaphragm function, and require a ventilator to breathe.
- C4: May retain some use of biceps and shoulders, but weaker.

- C5: May retain the use of shoulders and biceps, but not of wrists or hands.
- C6: Generally retain some wrist control, but no hand function.
- C7 and T1: Can usually straighten their arms but still may have dexterity problems with hands and fingers. C7 is generally the level for functional independence, because the user will be able to control a wheelchair.

A person with an incomplete injury retains some sensation or movement below the level of the injury. And, while less than 5% of people with "complete" spinal cord injury recover locomotion, over 95% of people with "incomplete" spinal cord injury recover some locomotory ability. Figure 10 shows which parts of the body may be affected by paralysis and loss of function in case of full spinal cord injury. An initial study suggested the most suitable potential users that ASIBOT robot could address, ranging from C2 to C7.

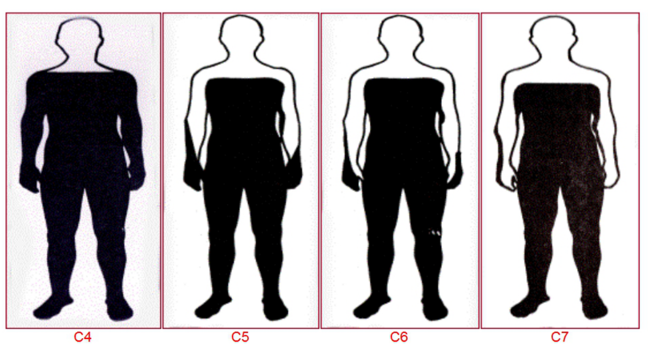


Fig. 10. In black is represented the lack of sensorimotor functionality

On the other hand, interface device specification is variable. Interaction devices address several trade-offs and complications, making some devices mutually exclusive. A thorough analysis of several HMI techniques can be found in literature [16]. Nevertheless, Table I shows a list of interface devices versus upper limb mobility, from different motion impaired levels and residuals. Each column shows a group of target users, and rows show the usability of several kinds of interface devices. Mobility capacities are ordered from left to right in ascendant order of disability, from those users that are able to move lower limbs, to those with a high degree of motion impairment. The letter in the first column refers to the output format of the device actuated by the user. The nomenclature used in this column is the following.

- 'C' represents a command type output, generated by software running on the PC, PDA, or any mechatronic device able to generate high-level protocol commands.
- 'O' refers to simple devices like switches, licorns, or push-buttons that are physically connected to a control unit (PC, PDA, or similar).
- 'P' refers to all analogue, transducer-based devices like joysticks. Devices activated by a single hand or foot, chin, back of neck, etc, in which a proportional control requires dexterous control of the related movement, are included in this category.

TABLE I
INTERFACE VS. DISABILITY CLASSIFICATION

Affected Mobility vs. Interface	No leg mobility	No upper nor lower limbs	No head, neck nor feet mobility	Only vision, hearing, and voice	Only vision and hearing
PC, keyboard, and mouse (C)	Yes	No	No	No	No
PDA + pointer (C)	Yes	No	No	No	No
PDA + tactile screen (C)	Yes	No	No	No	No
2D/3D hand joysticks (P/C)	Yes	No	No	No	No
Tactile input/ haptic output devices (P/C)	Yes	No	No	No	No
Single switch handled screen interfaces (O)	Yes	Yes	No	No	No
Head, shoulder or hand gesture recognition (C)	Yes	Yes	Yes	No	No
Head/shoulder activated Joysticks (P/C)	No	Yes	No	No	No
EMG, *Eyes or gaze tracking* (P/C)	Yes	Yes	Yes	Yes	Yes
EEG-BCI (C)	Yes	Yes	Yes	Yes	Yes
Facial command recognition (C)	Yes	Yes	Yes	Yes	Yes

However, dependability of a complete system for human-robot cooperation is dominated by the safety issues. Taking this into account, the simplest solution to cover the users' needs and expectations should be considered the most reliable and useful for the physically impaired. For the sake of user safety, we assume that the user is always in the control loop, at least with the role of supervisor, and can override the current control actions in case he or she is not satisfied with the system behavior.

D. ASIBOT safety

Safety issues are a key factor in rehabilitation robotics. Assistive robots need to operate close, and sometimes in contact, with humans. The ASIBOT safety strategy is based on the following set of factors:

- Velocity control: The robot velocity is limited on each axis controller and adjusted to achieve a balanced trade-off between fast transition movements and slow actions when near the user.
- Safety under power off: The entire system is prepared to be safe during power off thanks to the motor brakes and the DS's passive design, as no energy is required for a tip to remain attached to a DS.
- Software safety motion control: Software implements a Dead Man Switch (DMS) feature by default, for the sake of the user's safety. Any physical movement of the arm, either in pre-programmed tasks or in direct control,

requires the DMS to be kept pressed to be performed. Any time the user relieves pressure from the DMS, the movement stops. Other safety measures include security volumes (the zone defined around the user where the robot can never pass, so undesired collision is avoided), and the robot's base locking system, that assures that it is impossible to release one docking mechanism until the next one is safely locked to the DS.

The trade-off between safety and performance is the key issue in the domain of physical Human-Robot Interaction (pHRI). In pHRI, accurate positioning is secondary to "natural", soft interaction. Additionally, in assistive devices, time to perform a task is not so critical: slow motions are welcome. As an assistive robot working in cooperation with humans, priority is to assure a totally secure Head Injury Coefficient (HIC) [17]. As a climbing robot itself, safety must be guaranteed considering that the force of gravity on the robot depends on its position: on the wall, on the ceiling, or on the table. The robot must be safe in every 3D position in the environment.

Due to the complexity of DLA execution in unstructured and dynamic domestic environments, and the unpredictable or unexpected behavior of a user during task execution, safety must also be granted by means of mechanically safe robots. The limitation in overall weight and inertia is a common design point for climbing robots. This factor is intrinsic in ASIBOT's design, providing extra security.

III. Tests with impaired users at HNPT

This part of the article presents a usability assessment of ASIBOT helping the severely disabled, developed as part of the ASIBOT Program at the Universidad Carlos III de Madrid in collaboration with the FUHNPAIN, the Foundation for Research and Integration at the National Paraplegic Hospital in Toledo (Hospital Nacional de Parapléjicos de Toledo, HNPT). This is a national reference center that specializes in comprehensive treatment for people with spinal cord injuries, a physical affliction with several degrees of affection depending on the level and location of the trauma.

Our aim was to gather structured data from the experiment reflecting opinions about using the robot, focusing on the detection of acceptance level, identifying prejudices and fears, uncovered needs and expectations [18], [19]. We also aimed at generating new ideas from the users' opinions to serve as a base for improving the design of new prototypes.

A. User selection criteria and pilot test

The user selection criteria was strictly based on rehabilitation doctor expertize. The target population studied was composed by patients who had had spinal cord injuries for at least a year. No cases of patients with extremely acute injuries were considered. Focus was put on users whom, once past an initial phase, had spent regular periods of time in their homes, which gave them a perspective on the main difficulties they could encounter in their daily lives. Because of their daily experience in facing numerous problems of dependency, they were able to evaluate the functionality of technical aids with more objectivity. Only patients affected at the cervical level, from neurological levels C4 to C7, were chosen, as the resulting limitations affect their upper extremities, yet do not eliminate the possibility of using the different interfaces for the proposed tests. Additional exclusion criteria were: epilepsy, mental retardation, uncorrected visual deficiency, or psychiatric problems. The final group that was selected for performing the tests was composed by the five hospital patients who fulfilled the described criteria. Regarding the number of users for a proper usability assessment, Virzi [20], and more recently Lewis and Turner [21], [22] have published influential articles on the topic of sample size in usability testing. According to these authors, five is a proper number for usability testing.

The experiment procedure included a pilot test prior to the tests in real settings in order to assess different modes of robot-user interaction. These were implemented through a graphical user interface on a PDA where six different options were given, in the form of large visual-tactile buttons, each to command a different potential robot task to be performed: shave, fill a cup, feed, iron, clean, dress. The following modes of interaction were implemented (sorted according to the degree of mobility required for their use, from most to least):

- Tactile: task selection via the user's touch or a pencil, double-touch to validate.
- Joystick: movement through joystick for task selection, pressing a button for validation.
- Voice recognition: tactile or joystick options for task selection, validation by voice recognition.
- Turning on sequence: the selected task changes automatically every certain time, validation by pressing a button.

These mechanisms were the selected as potential interfaces with the robotic system given they are the most commonly accepted among the user interface community [23], [24]. The users were then asked to give their opinion on each interface, focusing on easiness of use, practicality, and how appropriate they found each interface taking into account their own individual capabilities.

B. Scenario and task selection for tests

At this stage, the users were queried on which activities they found most unpleasant and would like to be able to perform without depending on another person, regardless of whether the robot could do them or not. Getting dressed and personal hygiene were the most commonly mentioned tasks. Additional mentioned tasks included cleaning the house, cooking, making or unmaking the bed, folding sheets, dressing, and tasks that require additional accuracy such as shaving, cutting nails, combing hair, picking up glasses, opening windows, and opening doors. The users were then asked to set their order of priority on four settings that we proposed. These settings were based on the tasks that they had proposed and basic feasibility factors. The results, from highest priority to lowest, were the following:

1) Personal hygiene: washing one's face and hands, brushing teeth, combing hair, shaving, applying make-up...
2) Lying in bed: bringing small objects near...

3) On the wheelchair: eating, drinking, bringing small objects near...
4) In the kitchen: opening cupboards, moving utensils...

Given the fact that personal hygiene was the preferred setting for the robot in terms of this priority rating, the selected environment for the tests was a bathroom scenario. Five tasks were selected from among the users' proposals, taking into account feasibility, time consumption, and easiness to setup criteria: (a) drinking, (b) brushing one's teeth, (c) putting make-up on or drying one's face, (d) washing one's face, and (e) picking objects up.

C. Test setup and necessary adaptations

The adaptations for the selected activity tests at the bathroom scenario were minimal. As a first step, a simulated version of the environment was developed using the MATLAB VRML toolbox. Using this simulated environment, the optimum number of DS, and their location and orientation were determined. Only two DS were determined to be needed. Additionally, safety areas were set (as seen in Figure 11), to be used to avoid undesired robot-user and/or robot-environment collision.

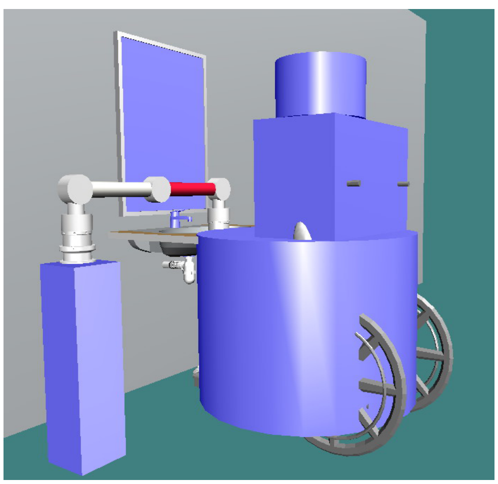


Fig. 11. Bathroom safety area representation on 3D VRML model

The main physical task was the mechanical installation of the DS needed to perform the desired tasks. The two DS were fixed using a steel structure, locating one at each side of the sink as seen in Figure 12.

Fig. 12. Bathroom at HNPT's pilot home, before and after adaptations

Even though each robot tip has a gripper with three fingers, the shape, size and texture of an object can make its manipulation very difficult. This is especially notable in household environments such as a bathroom, where common objects such as soap are extremely difficult to work with. In order to solve this issue, the rapid-prototyping adapted tool mechanism was used. Several new tools were developed for the robot, meant to be attached by the same bayonet system used in the docking process. The following set of adapted tools was developed: an electric shaver, an electric toothbrush, a make-up brush, a cup, a sponge, and a bottle. Figure 13 depicts some of these adapted ASIBOT tools.

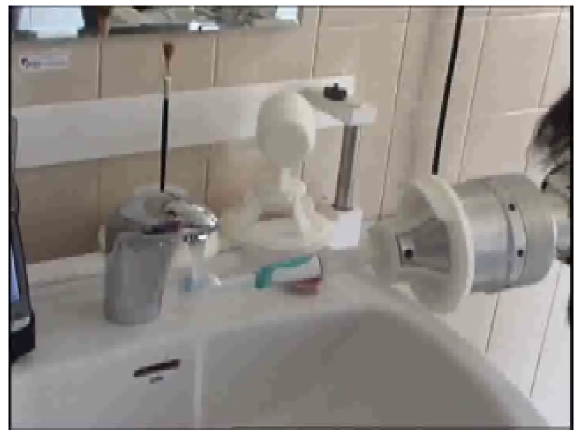


Fig. 13. Toothbrush toolholder in use; cup and make-up brush in background

The position over the shelf was selected for tool exchanging, and an automatic soap dispenser for the cleaning task with the sponge tool was installed. Another modification was the substitution of the classic faucet by an automated infrared one. This is an example of a universally accessible product. The robot activates the faucet by approaching with the toothbrush, the same way a user with enough mobility would.

D. Bathroom scenario performance test and results

The robot's features and HMI capacity were evaluated individually by each user, who expressed their opinions via a range of satisfaction scores, from -2 to +2.

Table II summarizes the user's questionnaire and results on specific tasks. It can be seen that simple tasks such as giving the user something to drink achieve relatively high rankings. Table III summarizes the user's questionnaire and results on the robot itself. The top ratings refer to aspects of ease of handling, how quickly it worked, and its multi-use functionality.

The users were finally asked what changes they suggested to make the robot more useful. The most common suggestions were a smaller size, greater ease in robot mobility, and complete recognition of the user's natural speech. Moreover, the overall impression was that users significantly appreciated the chance of performing DLA's by themselves using the ASIBOT assistive robot as an aid: partially recovering personal autonomy, and gaining self-esteem.

TABLE II
USERS' QUESTIONNAIRE RESULTS (MEAN/MODE)

Tasks (according to section III-B)	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**
Does the robot help you?	0,84/2	0,8/1	0,8/1	1,33/2	1,2/2
Is it useful and easy to use?	1,2/2	0,6/1	0,7/1	0,66/2	0,84/1
Do you need another aide using the robot?	0,8/1	0,33/1	0/-1	0,14/1	1,2/1
Is the robot able to increase your autonomy?	1,4/1	0,5/0	0,2/-1	0,66/2	0,8/1
Does its use imply physical or mental effort?	1,4/2	0,66/1	0,33/1	0,33/1	0,5/1
Does the robot perform desired tasks successfully?	1,8/2	0,16/0	1,66/1	1,3/1	0,4/1
Do you feel motivated to use it for this activity?	1,2/1	0,8/0	0,7/1	0,6/1	0,6/0
Overall impression	2	1	1	1	1

TABLE III
USERS' OVERALL VALUATION

TOPICS	**Mean / mode**
Aesthetic	0,65 / 2
Size, Range	-0.25 / 0
Easy to use	0,83 / 1
Operation Speed	1,54 / 2
Safety	0,82 / 1
Robustness	1,85 / 2
Easy setup	1,20 / 1
Overall impression	1 / 1

IV. ASIBOT KITCHEN ENVIRONMENT TEST-BED

After having performed the hospital tests, a test-bed to continue research on performing DLA's in household environments was developed. This test-bed is a kitchen scenario that contains real household appliances, in addition to features that faithfully represent a real home environment prepared for impaired users (counter height prepared for use of a wheelchair, automated shelves, presence sensors...). It is essentially a complete living space ready to be used by impaired and non-impaired users. The kitchen, additionally, is portable, as it is made out of demountable assembled modules. It is currently located at University Carlos III de Madrid's Technological Centre, more specifically, in the Assistive Robot Laboratory. The kitchen's free surface ranges approximately 19 m^2.

The fully furnished kitchen is now provided with fixed and rail-mounted DS's to support ASIBOT's fixation and energy requirements. The number of DS's was minimized while still optimizing the robot reach volume. Two of the total of six installed DS's can be seen in Figure 14 (both large circles). The physical installation of DS's among the kitchen has not reduced the kitchen's functionalities.

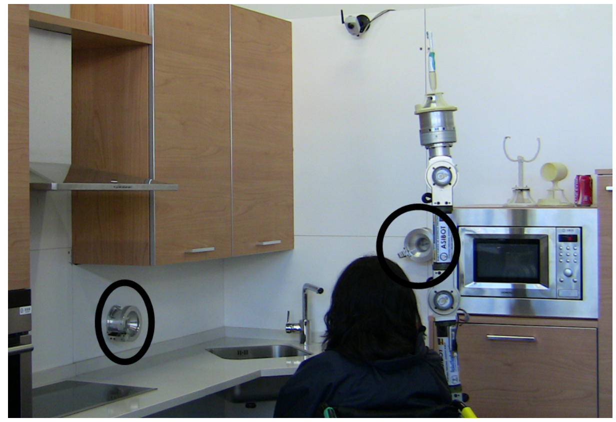


Fig. 14. The ASIBOT kitchen environment test-bed

A. ASIBOT kitchen test-bed simulation and integration

The authors have recently developed a virtual ASIBOT and kitchen test-bed simulation environment. It is based on the Open Robotics Automation Virtual Environment (OpenRAVE) [25] core libraries. The underlying idea is to provide a low cost virtual environment to allow performing tests with time savings and effectiveness. It is currently used for research in planning and learning, and in addition serves as a practical platform for:

- Robot on-line and off-line task programming (correction of errors, safety issue testing as provided by virtual safety volumes shown in Figure 15).
- Robot prototype and tool adaptation design (physical dimensions, weight, manipulability).
- DS optimizer for determining number, location (on furniture, over the cooking top, ceiling hanged...), and type (fixed, rail mounted, wheelchair mounted...) of DS's.
- Demonstrator for potential users and caregivers.

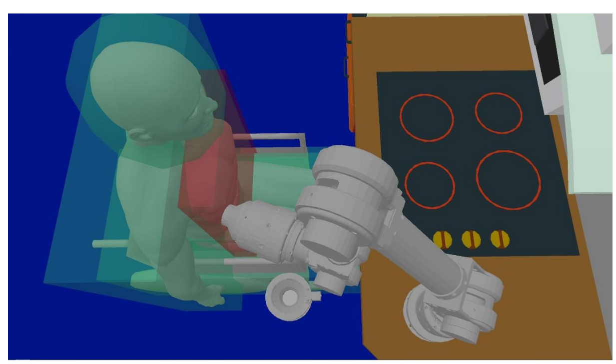


Fig. 15. Scene of collision with user safety volume computed during simulation

The simulated kitchen environment, HMI devices, and the real robotic system have been integrated into a common software architecture, YARP [26]. YARP is used because of its light weight, multi-platform support, simple API, and bindings for many programming languages [27]. Another benefit is that connections are made seamlessly: commands can be sent to the robot, the simulation, or to both (simultaneously) due to the common interface and publisher/subscriber paradigm implementation.

B. Assistive-living devices and sensors

Standard domotic devices connected by an EIB bus have already been introduced to explore cooperation between assistive devices. They are accessible through a software gateway that communicates with the robot network. Additionally, embedded devices are being adapted to interface kitchen electrical appliances to the common services architecture. Four IP-server surveillance cameras have been set in strategic locations to send raw image data to be processed by the room controller. These devices are linked by exchange services and keep tabs on each other and the user. Photogrammetric algorithms are being applied to discover absolute Cartesian coordinates of objects of interest for the user. Images received from the environmental cameras are processed by color segmentation, and centroids are calculated through standard machine vision algorithms. Full algorithms have recently been published by some authors of this paper [28]. Figure 16 shows an example of the results of these process. The absolute Cartesian coordinates of localized objects are transformed into coordinates that are useful to the robot.

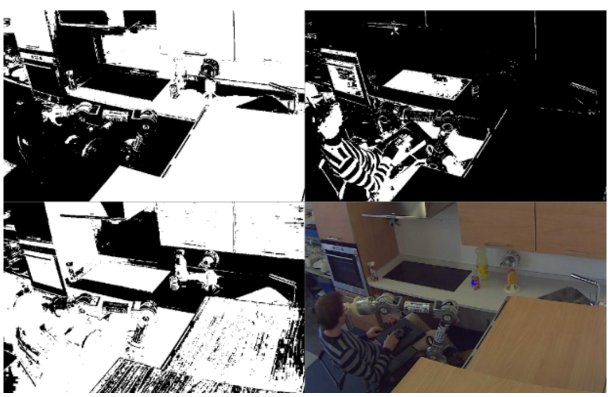


Fig. 16. Color segmentation and object centroid on kitchen IP camera image

V. Conclusions

Until now, two adapted environments specially designed to support motion impaired have been adapted. These scenarios, a bathroom and a kitchen, have been adapted with minimal modifications: strategically localized DS, and optional toolholders, IP environment cameras, and extra sensors. The first environment to be adapted was the bathroom of the DLA Occupational Therapy apartment located at the Hospital Nacional de Parapléjicos de Toledo installations. The second one, a kitchen environment test-bed, has been assembled at one of Robotics Lab's laboratories. This place will integrate and establish a common framework for several research groups and University related enterprises interested in technology transfer. The future work scenario would coordinate the efforts of many researchers and stakeholders organized in user targeted multidisciplinary teams to design, develop and evaluate technical aids and system. The common objective is to preserve and increase the personal autonomy of its users.

ASIBOT's ability to move around the house between fixed or mobile stations has been deeply tested, and clinical trial has discovered its usefulness to assist motion impaired to perform a wide variety of tasks by themselves: eating, cleaning, washing, handling, etc. But previous-programmed based behavior is not enough to meet the user's expectations, and deep usability improvement areas have been detected. The next version of the ASIBOT robotic system aims to be a safe and reliable domestic robot assistant with its mechatronic design, force-torque sensing, cameras at tips, and integrated control along the entire robot structure. Our target is to develop and test a new light-weight domestic climbing robot specifically designed and programmed for human-robot interaction in domestic environments, "dependability-proven" and ready to be used by anyone, in a customizable personal way. Extensive experimental and clinical trials and direct user implications on design stages will be continued to find definitive, widely accepted solutions.

Acknowledgment

Special thanks to the Robotics Lab team: Raul Correal, Raul Palencia, Victor Placer and many others. Without their help it would have not been possible to develop the ASIBOT trials. This work had been funded by the EU community under project IST-2001-32080. Funding for these trials was provided by the IMSERSO (Social Service National Institute) of Spanish government. The authors would also like to acknowledge the work of the other partners involved in these projects.

References

[1] M. Matarić, J. Eriksson, D. Feil-Seifer, and C. Winstein, *Socially assistive robotics for post-stroke rehabilitation*, Journal of NeuroEngineering and Rehabilitation, 2006.

[2] A. Jardón, *Assistive robot design methodology. Application to portable robot ASIBOT*, Doctoral Thesis, Supervisers: C. Balaguer, and A. Giménez, Sobresaliente "Cum Laudem", 2006.

[3] A. Jardón, A. Giménez, R. Correal, R. Cabas, S. Martínez, and C. Balaguer, *A portable light-weight climbing robot for personal assistance applications*, Industrial Robot: An International Journal, Vol. 33, No. 4, pp. 303-307, 2006.

[4] Topping M, *Early Experiences Encountered in the Placement of 60 Handy 1 Robotic Aids to Eating*, In Proc. of the IEEE 93 Conference on Cybernetics, Le Touguet, France, 1993.

[5] Exact Dynamics, http://www.exactdynamics.nl/. *Last access March 23rd 2011.*

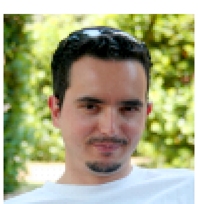
[6] Z. Bien, M. Chung, P. Chang, D. Kwon, D. Kim, J. Han, J. Kim, D. Kim, H. Park, S. Kang, K. Lee, and S. Lim. *Integration of a Rehabilitation Robotic System (KARES II) with Human-Friendly Man-Machine Interaction Units*, Autonomous Robots 16, pp. 165191, Kluwer Academic Publishers, 2004.

[7] E. Chaves, A. Koontz, S. Garber, R. Cooper, and A. Williams, *Clinical Evaluation of a Wheelchair Mounted Robotic Arm*, Technical report, Univ. of Pittsburgh, 2003.

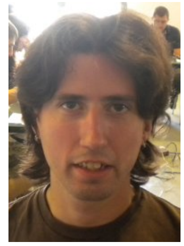
[8] H. Tijsma, F. Liefhebber, and J. Herder, *Evaluation of New User Interface Features for the Manus Robot ARM*, In IEEE Int. Conf. on Rehab. Robotics, pages 258263, 2005.

[9] M. Nechyba and Y. Xu, *SM2 for new space station structure: Autonomous locomotion and teleoperation control*, in Proc. IEEE Int. Conf. Robotics and Automation, San Diego, CA, May 1994, Vol. 2, pp. 17651770.

[10] C. Balaguer, A. Giménez, and M. Abderrahim, *A climbing autonomous robot for inspection applications in 3D complex environment*, Robotica, Vol. 18, No. 3, pp. 287297, Sept. 2000.
[11] Dallaway JL, Jackson RD, *The RAID workstation for office environments*, in Proc. of the RESNA 93 Annual Conference, pp. 504-506, 1993.
[12] C. Balaguer, A. Giménez, and A. Jardón. *Climbing Robots' Mobility for Inspection and Maintenance of 3D complex Environments*, Autonomous Robots, Vol. 18, No. 3, pp. 157-169, 2005.
[13] R. Cabas, and C. Balaguer, *Design and development of a light weight embodied robotic hand activated with only one actuator*, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'2005), Edmonton, Canada, Aug., 2005.
[14] R. Cabas, L.M. Cabas, A. Jardón, C.Balaguer, *Optimized design of the underactuated robotic hand*, Int. Conference on Robotics and Automation (ICRA 06), Orlando, United States, May, 2006.
[15] C. Balaguer, A. Giménez, A. Jardón, R. Correal, and S. Martínez. Advances in Telerobotics. Chapter:*Proprio &* Teleoperation of a robotic system for disabled persons' assistance in domestic environments. *pp.389-402. ISBN: 978-3-540-71363. Springer Tracts in Advanced Robotics (STAR)*, vol. 31. 2007.
[16] R. Rammoun, J.M. Détriché, and F. Lauture, *The new MASTER man-machine interface*, Int. Conf. on Rehabilitation Robotics.
[17] A. Bicchi, and G. Tonietti, *Fast and "soft-arm" tactics [robot arm design]*, Robotics & Automation Magazine, IEEE , Vol. 11, No. 2, pp. 22-33, June 2004.
[18] L. Demers, and B. Ska. *Item analysis of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST)*. Assistive Technology, 2000; 12:12-96, 2000.
[19] L. Demers et al. *An international content validation of the Quebec User Evaluation of Satisfaction with assistive Technology (QUEST)*, Occupational Therapy International 6(3) (1999), 159-175, 1999.
[20] R.A. Virzi. *Refining the test phase of usability evaluation: How many subjects is enough?*, Human Factors 1992; 34:457-468.
[21] Lewis JR. *Evaluation of procedures for adjusting problem-discovery rates estimated from small samples*, International Journal of Human-Computer Interaction 2001; 13:445-479.
[22] Turner CW, Lewis JR, Nielsen J. Determining usability test sample size. International Encyclopedia of Ergonomics and Human Factors 2006; Second Edition, 3:3084-3088.
[23] H. Eftring, *Robot control methods and results from user trials on the RAID workstation*, Int. Conf. on Rehabilitation Robotics, 1994.
[24] Z. Han, H. Jiang, P. Scucces, S. Robidoux, and Y. Sun. *PowerScan: a Single-Switch Environmental Control System for Persons with Disabilities*, Proc. of the IEEE Bioengineering Conf. 8-9th, 171-72, 2000.
[25] R. Diankov. *Automated Construction of Robotic Manipulation Programs*. Carnegie Mellon University, Robotics Institute, (2010, August), Available from http://openrave.programmingvision.com
[26] P. Fitzpatrick, G. Metta, and L. Natale. *Towards long-lived robot genes*, Robotics and Autonomous Systems (2008), 56(1), 2945.
[27] J.G. Victores. *Software engineering techniques applied to assistive robotics: guidelines & tools*. *Master Thesis*, Supervisers: A. Jardón and C. Balaguer. Sobresaliente "Cum Laudem", Oct., 2010.
[28] J.G. Victores, A. Jardón, M.F. Stoelen, S. Martínez, and C. Balaguer. *ASIBOT Assistive Robot with Vision in a Domestic Environment*, Robocity2030 7th Workshop, Móstoles, Spain, Visión en Robótica. ISBN: 84-693-6777-3. Universidad Rey Juan Carlos, pp. 61-74, Oct., 2010.



Alberto Jardón Huete finished his Ph.D. degree in Electric, Electronics and Industrial Automation Engineering (2006). He received his B.Sc. in electronics engineering (1998) and is graduated in Electrical Engineering (2002) at University Carlos III of Madrid. He is an active member of the Robotics Lab since 1997, and has collaborated in the development of the climbing robots ROMA I, ROMA II, MATS/ASIBOT. Currently he is focused in the design and development of light weight service robots. His interests include assistive robotic design, mechatronics, robotic research, intelligent tuneling, the development of tools to perform this research and the transfer of robotics technology to industry.



Juan G. Victores is an Industrial Engineer specialized in Electronics and Automation. Degree received from the University of Vigo in 2008. Student of Ph.D. in Automation and Robotics. He participated, as technician, in the EU robotics in construction project TunConstruct between 2007 and 2008. Ever since, he has been an active researcher for ASIBOT project, and additionally contributes to several Open Source projects currently hosted at Sourceforge.net.

Santiago Martínez is a Electrical Engineer specialized in Electronics and Automation. Degree received from the University Carlos III of Madrid in 2005. Student of Ph.D. in Automation and Robotics. He participated, as technician, in the EU robotics project MATS between 2004 and 2005. Since he received his degree is working into the 6FP IP ManuBuild project as researcher.

Antonio Giménez studied electrical engineering at the Polytechnic University of Madrid, Spain, and received his Ph.D. from the University Carlos III of Madrid, Spain, in 2000. He is an associated professor at the University of Almería. He has participated in numerous national and international research and development projects. His research interests include: design and robot development, rehabilitation robots, climbing robots, and automation in construction. He has published numerous refereed publications in international journals and conference proceedings.

Carlos Balaguer received his Ph.D. in Automation from the Polytechnic University of Madrid (UPM), Spain in 1983. From 1983-1994 he was with the Department of Systems Engineering and Automation of the UPM as Associated Professor. Since 1996, he has been a Full Professor of the Robotics Lab at the University Carlos III of Madrid. He is currently the Vice-chancellor for research of the university. Prof. Balaguer's research has included robots' design and development, robot control, path and task planning, force-torque control, assistive and service robots, climbing robots, legged and humanoid robots, and human-robot interaction.

He participates in numerous EU projects since 1989 , like Eureka projects SAMCA, AMR y GEO, Esprit projects ROCCO and CEROS, Brite project FutureHome, IST project MATS, and the 6FP IP projects ManuBuild, I3CON and Strep Robot@CWE. He has published more than 180 papers in journals and conference proceedings, and several books in the field of robotics.

He is a member of IEEE and IFAC, and former President of IAARC (2001-2004). He participates in the European networks Euron and Clawar. Prof. Balaguer had been also an Associate Editor of IEEE Roboticsand Automation magazine (2000-2005) and is member of the Editorial Board of Automation in Construction journal (Elsevier). Currently he is the coordinator of the Spanish Robotic Network and of the Madrid Community universities' project RoboCity2030 on Service Robots, and is the Spanish representative in the European platform EUROP.