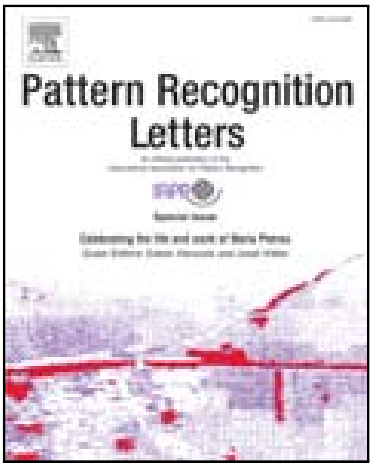

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**Highlights**

- Our main goal is to improve assistive robotics platforms using an adaptive HRI system
- We provide an affordable and natural human-robot interface using multi-sensor data
- It allows interactively and customizable rehabilitation therapies for disabled people
- It is integrated in a mobile robotic platform which is being tested in a hospital
- We designed apps to improve cognitive capabilities of people with brain damage

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# A robotic platform for customized and interactive rehabilitation of persons with disabilities

Francisco Gomez-Donoso[a], Sergio Orts-Escolano[a], Alberto Garcia-Garcia[a], Jose Garcia-Rodriguez[a], John Alejandro Castro-Vargas[a], Sergiu Ovidiu-Oprea[a], Miguel Cazorla[a,**]

[a] *Instituto de Investigación en Informática*
*University of Alicante*
*PO. Box 99, E-03080 Alicante, Spain*

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ABSTRACT

In this work, we have developed a multisensor system for rehabilitation and interaction with persons with motor and cognitive disabilities. The system enables them to perform different therapies using multiple modes of interaction (head and body pose, hand gestures, voice, touch and gaze) depending on the type and degree of disability. Through a training process, the system can be customized enabling the definition of patients' own gestures for each sensor. The system is integrated with a range of applications for rehabilitation. Examples of these applications are puzzle solving, mazes and text writing using predictive text tools. The system also provides a flexible and modular framework for the development of new applications oriented towards novel rehabilitation therapies. The proposed system has been integrated in a mobile robotic platform and uses low-cost sensors allowing to perform non-intrusive rehabilitation therapies at home. Videos showing the proposed system and users interacting in different ways (multimodal) are available on our project website www.rovit.ua.es/patente/.

## 1. Introduction

Modern societies face various societal challenges related to different aspects of life such as health, demographic change, and well-being. It is no coincidence that a considerable amount of funding is being devoted to such areas by international programs, such as, the European Framework Programme for Research and Innovation Horizon 2020.

Nowadays, the design and development of care systems for dependent persons is one of the top priority research fields in almost every developed country. This is because dependency situations arise in a wide range of age groups for various reasons, including aging, congenital diseases, or road accidents, to name a few. The system proposed in this study has been jointly developed with experts in brain injury from the Hospital of Seville. These specialists deal with one of the main causes of dependency: acquired brain damage. Given its high incidence rate, this impairment is now considered a significant public health problem. Acquired brain damage refers to traumatic brain injury and cerebral palsy, which often cause motor and cognitive issues so that rehabilitation is required to recover their functionalities. It is important to note that the system is targeted not only at patients with acquired brain damage, but also all kinds of persons affected by cognitive or motor disorders, such as, elderly persons.

The rehabilitation process involves taking care of patients, which usually consists of providing assistance and companionship to lonely people. Furthermore, the rehabilitation process has recently begun to be considered therapeutic. It is worth noting that such rehabilitation therapy is intended to be provided

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[**] Corresponding author: Tel.: +34-965-903400 ext: 2992; fax: +34-965-903902;
*e-mail:* `fgomez@dccia.ua.es` (Francisco Gomez-Donoso), `sorts@dccia.ua.es` (Sergio Orts-Escolano), `agarcia@dtic.ua.es` (Alberto Garcia-Garcia), `jgacia@dtic.ua.es` (Jose Garcia-Rodriguez), `jacastro@dtic.ua.es` (John Alejandro Castro-Vargas), `soprea@dtic.ua.es` (Sergiu Ovidiu-Oprea), `miguel.cazorla@ua.es` (Miguel Cazorla)

in situ at each patient's home in order to minimize therapy costs and effort. There are numerous studies showing the importance of using care or assistance robots on older and dependent persons. An overview can be found in (Broekens et al., 2009; Koceski and Koceska, 2016), which mainly shows the benefits of applying this kind of technology.

The aim of this paper is to propose a flexible robotic system for rehabilitation of dependent persons with motor or cognitive impairments. This system is focused on helping persons with disabilities to overcome various challenging situations that may happen during the rehabilitation process, including, for example, the impossibility to use a computer or, in the case of more severe brain damage, helping to train intellectual, memory and physical capacities. It also helps to achieve a complete social integration by allowing patients to use a word processor or even an email client with customized gestures. To this end, the system requires multimodal human-robot interaction using a set of different sensors to enable therapy and care for various disability types and levels. **Moreover, the developed platform can assist people with mobility problems. For example, persons with acquired brain damage often have mobility impairments and therefore, the platform we have developed is able to navigate through indoor environments and detect people, being able to move in front of the person who is going to interact with the robot to perform a therapy. However, if the person going to perform the therapy has no mobility disabilities, a static training station could also be deployed at the patient's house, with the patient positioned in front of the unit to perform the therapy.**

The rest of the paper is organized as follows: Section 2 reviews related works on assistance robotics and rehabilitation systems. Section 3 details the system proposed. Section 4 shows different application scenarios and applications that have been implemented using the system. Section 5 describes the evaluation of the system with an initial user study. In Section 6, we present system limitations and a discussion of the system proposed. Finally, Section 7 draws conclusions and directions for future work.

## 2. Related works

In the European Union, the issues we presented above have been widely discussed in the FP7 program. Previous systems include Companion-Able (Badii, 2015), which aims to take advantage of the synergy between robotics technology and ambient intelligence and their semantic integration in the environment of a caregiver. The same objective was pursued in the FLORENCE (Lowet, 2015), MOBISERV (Nani et al., 2015) and KSERA (Cuijpers, 2015) projects, which make use of an external sensor network, placing the robot in a structured indoor environment.

However, to be a true partner, robots need to be reliable, intelligent and able to work in close collaboration with humans (`http://cordis.europa.eu/ictresults`). The need to provide robots that can work with people (companion robots) is included explicitly in the heart of Challenge 2: ”Cognitive Systems and Robotics in the EU Framework Programme”. For example, the Hobbit project (Fischinger et al., 2016) develops a robot assistant to help seniors feel safe at home. Its main goal is to keep these older adults active with games and exercise, as well as detecting emergencies and acting accordingly. It focuses on falls, which are one of the leading cause of injuries among older adults. The robot is able to detect people in the environment and recognize whether they are lying on the floor (possible accident scenario). The system is not only able to recognize this situation, but is also intended to prevent it by implementing object recognition and grasping capabilities. This robotic platform exhibits a simple gesture interaction system. It allows users to point at objects that may be of interest for the user. The robot is able to provide these objects to the user. However, this robot lacks any features or skills that allow older or dependent persons to perform customized rehabilitation at home. Moreover, the GiraffPlus project (Coradeschi et al., 2014) proposes a complex system capable of monitoring the activity taking place in a house through a network of sensors (distributed around the house or in the body of an elderly person), together with a robot, which serves as an interface allowing different users, family members, caregivers or health staff, to virtually visit the elderly person.

RAMCIP (Kostavelis et al., 2016) is another recent European project that focuses on robot research to help people with mild cognitive impairment. One of its main research lines is the proposal of adaptive multimodal human-robot communication interfaces. This topic is a clear necessity for creating robots that can provide proactive assistance to elderly people. The RAPP project (Reppou et al., 2016) approaches the social exclusion of older people involving the use of assistive robots. They propose a software platform to deliver smart, user-empowering robotic applications, which for example, allow older persons to send emails with the assistance of friendly robotic platforms. (Matarić et al., 2007) propose a robot that allows simple therapeutic interactions with post-stroke patients in the process of performing rehabilitation exercises such as arm movements and shelving magazines. All movements are captured using an intrusive motion capture system based on electromagnetic sensors. Sensors are attached to the limb and arms, and are able to track movements from those parts of the body.

The Robot-Era project (Cavallo et al., 2012) implements and integrates a set of advanced robotic systems and ambient assisted environments in real scenarios to address common problems in the aging population. In addition, the consortium addresses social/legal plausibility and acceptability by end users. The system is used in real situations, cooperating with users to enable independent living and improve the quality of life and care of older adults. The GrowMeUp (Portugal et al., 2015) project also focuses on increasing the time span of independent and active living, and the quality of life, of older persons with mild physical or mental health problems. It provides an affordable robotic system that learns the habits and needs of older adults. It provides the following services: navigation, perception, people detection, emotion recognition, speech recognition, and adaptation to the user input. So far, this robotic platform lacks any other interaction mode apart from audio. Speech recognition is used to give instructions to the robot and it is able to synthesize and extract information as instructions or infer user emotions (anger, fear, happiness, disgust, ...). The mobile robot is able to react to the user input by using its stereo speakers.

Focusing more on specific systems for rehabilitation of persons with brain damage, we find number of studies in the current literature. (Lledo et al., 2016) proposes a therapy based on horizontal movements of the upper limb that have to be performed to complete the aims of the tasks, which consist of reaching peripheral or perspective targets depending on the virtual environment shown to the user. They study differences between using 2D and 3D user interfaces, concluding that 3D Graphical User Interfaces (GUIs) are still not comfortable enough for this kind of therapies in virtual reality. The neurorehabilitation system they use to perform the motor therapy is composed of a robotic system based on mechanical parts. Our proposal does not require physical interaction with sensors, apart from the tablet, allowing a more natural interaction. Their system is constrained to a limited number of movements based on their mechanical structures. Using vision sensors we are able to go beyond these constraints and facilitate a customized, natural interaction. Mechanical-based systems are more likely to be applied at the first stage of the rehabilitation process where users are still at the hospital and require assistance after an injury that has caused severe motor impairments. Currently, most of the research work has focused on providing physical assistance. However, recent rehabilitation studies state that new therapies that are not hands-on, and, therefore, do not require physical contact, are also extremely beneficial.

The majority of assistive robots that we have reviewed are constrained to specific users and scenarios, and as a consequence often fail when operating in dynamic, changing situations. It is very common for different users to have specific and changing requirements, in particular elderly and disabled persons. Most existing solutions for rehabilitation based on the use of the Kinect sensor (Lange et al., 2011, 2012; Fernandez-Baena et al., 2012) are constrained to a predefined set of body gestures, not being able to adapt to user needs. In addition, most of these platforms are conceived as static structures that require user adaptation. It is also important to emphasize that those existing works mainly focus on sports activities not suitable for persons with acquired brain damage and other brain-related disabilities.

Existing works that use computer vision for human-robot interaction and rehabilitation have mostly focused on the use of RGB-D sensors (similar to the Microsoft Kinect device). For example, in (Oliver et al., 2015), a system for carrying out rehabilitation of patients with acquired brain damage using RGB-D cameras is proposed. Although the main focus of this work is to assess the user experience, the proposed system is constrained to motor rehabilitation, only being able to recognize simple, basic gestures. Another system that uses the Kinect device to capture the movements of the patients during rehabilitation exercises is presented in (Freitas et al.). (Webster and Celik, 2014) presents an extensive review of Kinect applications in elderly care and stroke rehabilitation. They have classified most applications into groups of fall detection, fall risk reduction, Kinect-based rehabilitation methods, and serious games. Their main conclusion, is that some significant technological limitations still exist, such as having a fixed located sensor with a constrained range of capture, difficulty in fine movement capture and recognizing a predefined set of gestures.

In the literature, we can also find other related vision-based systems that use markers for allowing user tracking (Schönauer et al., 2011; Mead et al., 2010). However, these works are outside the scope of this review since most of them are intrusive, requiring wearable devices or markers, and the deployment of a large number of cameras (motion capture systems).

In this work, we propose a mobile robotic platform that enables natural and multimodal custom interaction for performing interactive rehabilitation of persons with disabilities. The proposed system is also used for keeping elderly persons active through the use of different applications such as memory and brain games, physical activities and other therapy programs. **The proposed multimodal interaction system and our adaptive framework are key factors for social and assistive robotics. We do not rely on default gestures that are recognized by the integrated sensors, such as Leap Motion, Kinect or EyeX, but we are able to learn and recognize patients' own gestures using a machine learning-based approach. Users can define their own gestures to interact with the proposed robotic platform and therefore, to carry out their therapies.**

**We believe that this is the first work that shows a rehabilitation robotic platform allowing multimodal interaction using a range of different computer vision sensors for precise hand tracking, body gesturing and eye tracking. Moreover, to the best of our knowledge, this is the first time that such a range of different interaction modes has been integrated for rehabilitation purposes.**

## 3. System

In our work, we propose a novel mobile robotic platform for custom, interactive rehabilitation of persons with different disabilities. The proposed system enables human-robot multimodal interaction by using a set of different sensors: 3D sensors, color cameras, microphones, eye tracker and a tactile interface.

Using information from these sensors we have created a platform that learns how users can interact with the system (custom gestures) based on their disabilities. Patients only require initial assistance from a caregiver or therapist for setting up the platform. Moreover, we have implemented a facial recognition system that allows the system to identify each user and load their previously learned profiles, adapting the way the user communicates with our system. When a person is detected, their preferences are automatically loaded into the system.

Below, we describe the different ways users can interact with the proposed system.

### *3.1. Physical setup*

All components are mounted on a mobile platform, forming a complete system for natural interaction. This system was

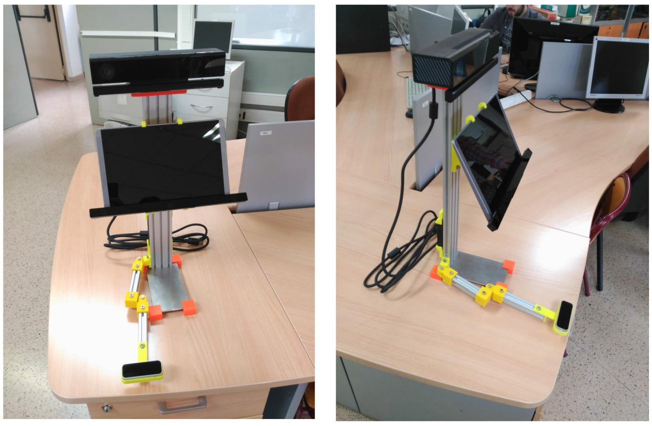

Fig. 1. Development platform.

recently deployed in a hospital in order to test the system on persons with disabilities. Figure 1 shows a prototype we used for development, but this set of sensors can be mounted on any robotic platform. For example, we are currently planning to integrate our system with the Pepper robotic platform [1] from Aldebaran robotics.

The proposed system uses a mid-range 3D sensor (Microsoft Kinect) mounted on top of the platform. As we will describe later, this sensor is used for people detection (Shotton et al., 2013) and body gesture recognition. Just below the 3D sensor, we mounted a digital tablet to display visual content. The digital tablet is also used for tactile interaction with the visual content, as part of users' rehabilitation process. This sensor allows people with motor or other severe disabilities to use their eyes as a virtual mouse to control user interfaces. On the top part of the digital tablet we have attached an array of microphones from the Kinect device that enables the system to receive voice commands. Finally, on the bottom part, there is a swivel arm with a short-range 3D sensor at one end. This sensor allows the user to interact with the system using precise hand gestures, such as air tapping or swiping. As we will see in the next sections, the proposed system is able to learn specific gestures to be performed using each available sensor. Figure 2 shows some diagrams of the proposed mobile robotic platform, application scenarios and one of the real platforms developed for this work.

### 3.2. Navigation and mapping

Although not the main focus of this work, it is worth mentioning that we have integrated previous works (Morell et al., 2014; Morell-Gimenez et al., 2014) we have developed for robot navigation and mapping into the mobile robotic platform. These techniques allow the robot to build a 3D map using three-dimensional data obtained by an RGB-D sensor. Using visual features and geometric information (planar registration) we are able to map the environment and create a downsampled map for navigation. In addition, we are also developing a framework for semantic localization (Rangel et al., 2016) that is being tested and integrated into the robotic platform. Figure 3 shows an example of a reconstructed map of an office at the University of Alicante.

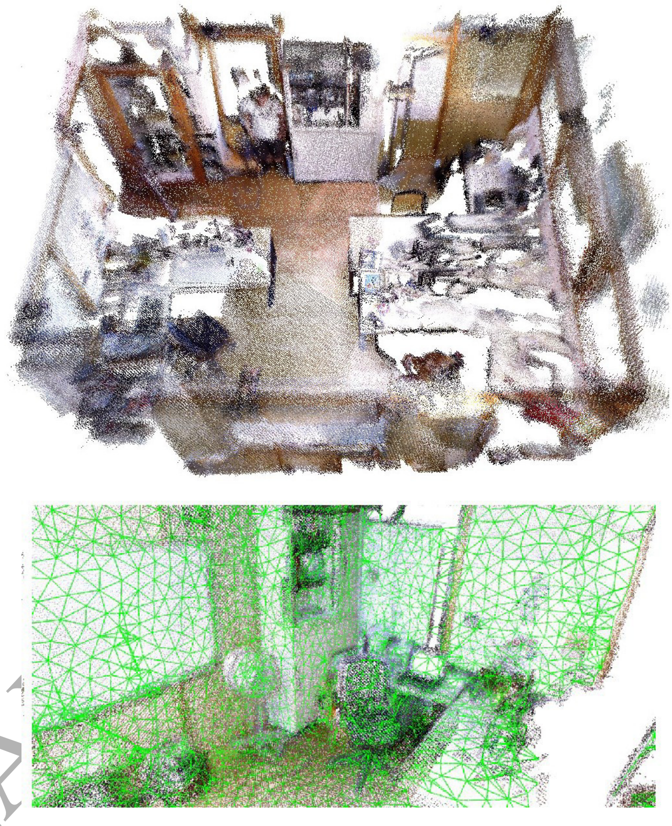

Fig. 3. Top: 3D map reconstruction of an indoor office (top view) using the robotic platform (RGB-D sensor). Bottom: Zoom-in screenshot of the scene and downsampled version of the reconstructed map (overlaid in green).

### 3.3. Body gestures

The first type of gesture that we can use to communicate with our system are body gestures. Using the Microsoft Kinect device, we are able to obtain and track up to 25 joints that represent our body pose, so we can define multiple gestures using every part of our body (ranging from gestures using our head to arms, hands, and even legs). Joint positions over time are used as input to our algorithms to learn new gestures that will be recognized by our system.

Moreover, we have developed a framework for learning custom gestures. This framework was first used for learning a subset of 11 gestures of Schaeffer's sign language (Gomez-Donoso et al., 2016) [2]. The system was able to successfully recognize this subset of gestures trained with multiple users. The main goal of this work was to provide a tool to help children with autism to communicate with the robotic platform by gestures

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[1] `https://en.wikipedia.org/wiki/Pepper_(robot)`

[2] Schaeffer's sign language consists of a reduced set of gestures designed to help children with autism or cognitive learning disabilities to develop adequate communication skills

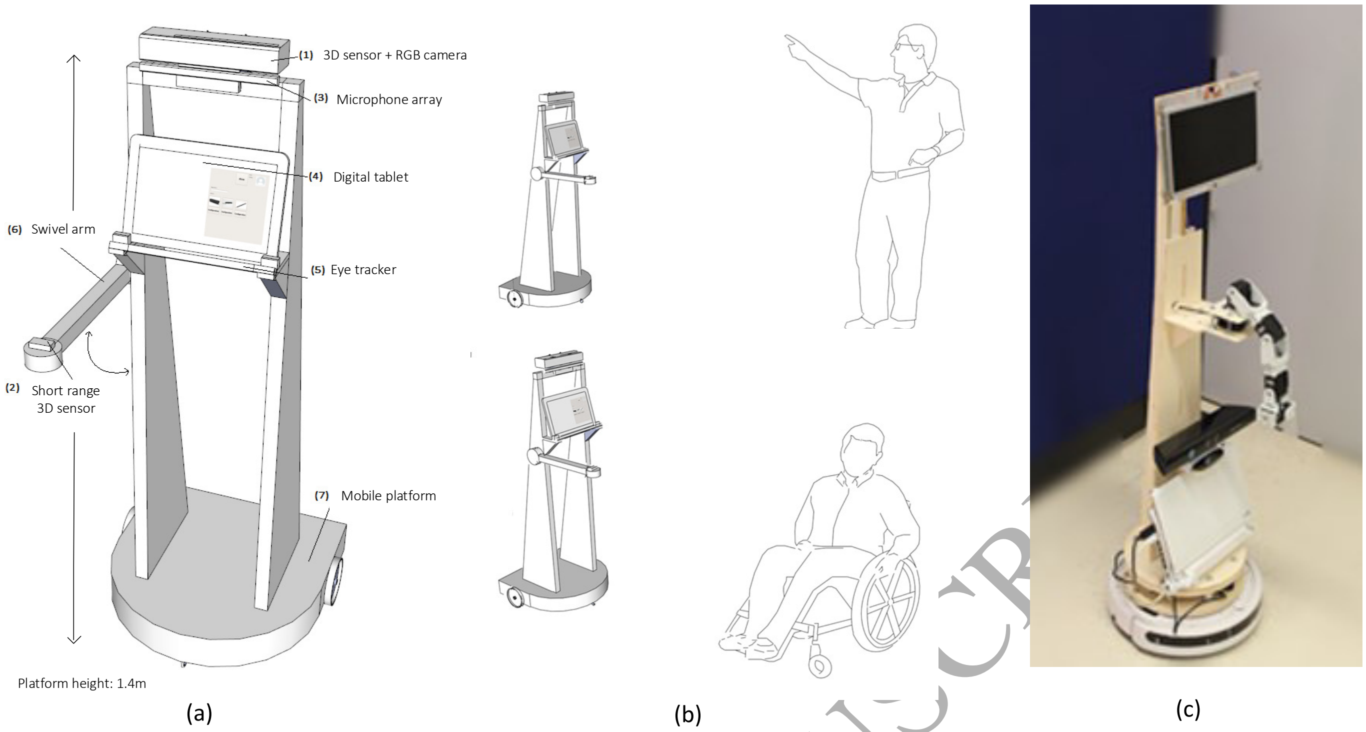


**Fig. 2. Diagram (a) shows a sketch of the proposed mobile robotic platform for performing customized rehabilitation at home. (b) Sketches of application scenarios. (c) A picture of the actual mobile robotic platform used during the development of the project**

and speech (see Figure 4). Users can express their feelings using a simple language automatically recognized by the robotic platform. Using the proposed system, people with autism can not only communicate with the platform but also carry out activities and games.

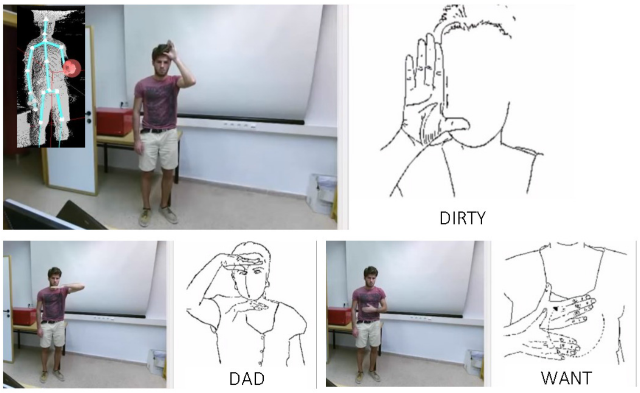


**Fig. 4. Example of a user performing body and hand gestures in front of the robotic platform. The proposed system can recognize a subset of Schaeffers gestures for human-computer communication. Top left: shows the 3D skeleton and tracked 3D joints used for recognizing the gesture performed. On the right part of each sub-image, we can see the gesture recognized by the system.**

### *3.4. Hand gestures*

Hands are an important tool for humans, arguably the most common way in which they interact with their environment. Therefore, we implemented hand gestures as another way of interacting with the proposed system. Using a short-range 3D sensor, we are able to precisely obtain and track a 3D representation of a user's hands. The proposed system is able to learn and recognize custom hand gestures as was previously demonstrated in Gomez-Donoso et al. (2016), but this time using coarse and fine hand gestures. Moreover, in order to allow natural interaction, we designed friendly interfaces avoiding strong constraints for human-robot interaction.

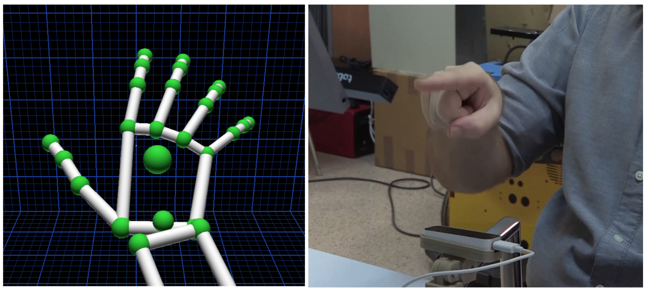


**Fig. 5. Left:3D representation provided by the Leap Motion sensor. It provides multiple 3D joints for tracking (green spheres). Right: example of a user interacting with the platform using the Leap Motion sensor (air tapping gesture)**

The Leap Motion sensor (LeapMotion) is mounted on a swivel arm, so patients can also interact using this short-range interaction mode (Figure 5). The robot can automatically move the arm in front of the user and use it as the main interaction mode.

By default, the proposed system can recognize three different gestures using this sensor: making a circle in the air to move to the next option on the graphical interface, move the hand down (tapping gesture, to click the current menu option) and finally, moving the hand up to return or go one level up in the option menu. Individuals who have suffered brain damage may not be able to perform any of these gestures, so the therapist can train the proposed system to redefine the gestures that the user or patient can perform. After repeating the gesture in front of the platform a couple of times, the system is able to learn and recognize the new gestures. These gestures are then associated with the current user for future interactions.

### *3.5. Eye tracking*

Another way of interacting with the proposed system is by using our eyes as a mouse. We have integrated a novel sensor (Tobii EyeX) that performs eye tracking and provides us with the position where the user is looking at the graphical user interface. It also provides us with the recognition of simple gestures such as blinking. Users are able to interact with our system by means of this sensor, which provides 2-dimensional positions of where the user is looking in the screen, allowing the selection of GUI items by simply looking at them. Moreover, we extended the interaction capabilities of the sensor, by using our framework for learning specific gestures performed by our eyes on the screen. By performing specific 2D shapes with our eyes on the screen, the system is able to learn these shapes or eye gestures and associate them with an specific action. We also implemented two different ways of emulating the click action. When the user is focusing on a button, we start a timer and if the user keeps the focus on that button, after a period of 2-3 seconds, the system clicks on that button. In a similar way, by detecting an eye gesture, e.g., winking, we can use it as the click action after the user has kept the focus on a specific button for a certain period of time.

Thanks to these additional features, we are able to provide persons with motor disabilities with a friendly way of interacting with our system, meaning they are able to navigate through the menus and to play puzzles and other rehabilitation games described later in this article.

### *3.6. Voice commands*

In our multimodal interaction system, we can also interact using simple voice commands. Using the speech recognition framework from the Kinect SDK we implemented the recognition of four basic voice instructions: next, previous, enter, and up. The system can also be trained to recognize other instructions to carry out specific actions that can be executed on the platform. As we previously mentioned for other sensors, we allow full customization of voice commands based on the user profile.

### *3.7. Tactile*

The main resource for displaying content is a digital tablet attached to the platform. The tablet also carries out data processing and input data gathering from the sensors described above. This renders the GUI, which allows visual interaction with the system. It also enables patients to carry out therapies based on activities such as solving puzzles, mazes and predictive text writing. We have developed a generic GUI that can be used with any of the interaction modes previously described. Figure 6 shows some screenshots of this GUI.

### *3.8. Framework for learning custom gestures using different sensors*

In order to learn and classify custom gestures using different sensors, our system allows the user to record other gestures instead of the default ones. To this end, a model containing all the recorded gestures for each sensor or type of interaction is stored. Each time the user records a new gesture, the information is stored and encoded in feature vectors depending on the kind of gesture or interaction, e.g., hand joint positions for hand gestures, or arm joints and angles for body interaction. In addition, the gestures are properly labeled to generate the model.

During classification time, these models are fed into the recognition system for inference. This system takes a gesture, which is properly summarized and encoded as a feature vector depending on the interaction mode, and sends it to a gesture class pre-selection module. This module executes a set of naive heuristics to discard improbable gestures and so generate a subset of possible candidates to increase both efficiency and accuracy during subsequent steps. Next, the subset of possible candidates and the gesture are sent to the classifier itself which compares the unknown gesture with every class of gesture in the model that is a possible candidate. The distance between input and candidate features is computed using the Dynamic Time Warping (DTW) algorithm by (Sakoe and Chiba, 1978). The Nearest Neighbor (NN) (Arya et al., 1998) algorithm is used to select the one with the shortest distance. The class of this gesture is returned by the system as the label for the user gesture.

### *3.9. System accessibility*

It is well known that the shape, color, size and position of elements are parameters that impact on the usability of every application. This is exacerbated when the GUI is used by persons with brain disabilities. With this in mind, we have implemented some features for improving both the usability and accessibility of the proposed system.

#### *3.9.1. Graphical User Interface color scheme*

We have defined an emerald and dark blue color scheme that increases the contrast of layout components such as buttons, text fields, and labels. Thanks to this color scheme, users can easily identify which button is in focus and when an action or an event is happening.

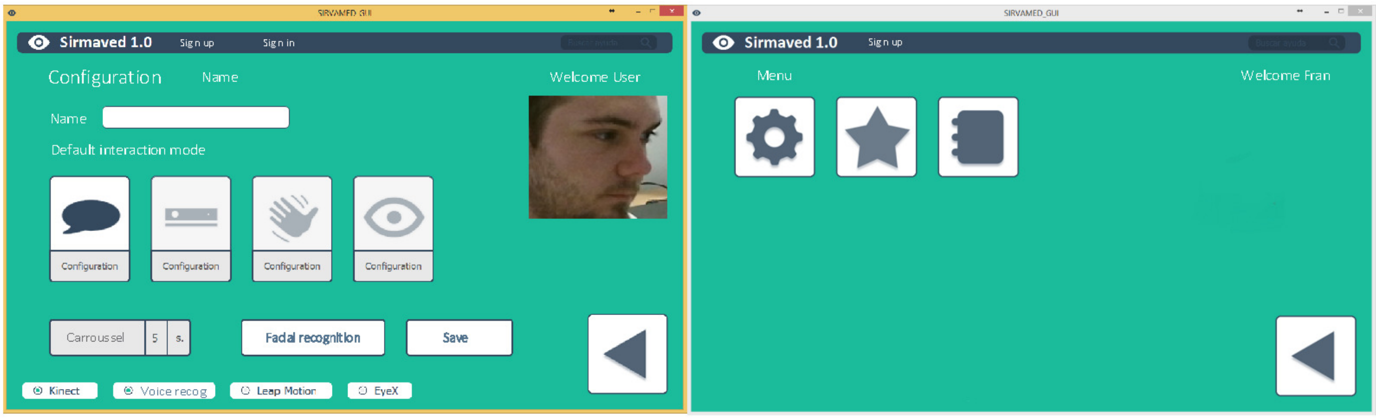


**Fig. 6. Left: Settings screen (Development mode: it shows user face and a quick menu on the bottom part for switching between interaction devices). By default, if the user already exists, it will automatically login using the existing facial recognition system and it will load the user profile, so preferred way of interaction is enabled by default. Otherwise, from the settings screen the user can create an account and configure settings for using the platform: preferred mode of interaction, facial recognition, etc. Right: Main screen. Once the user has logged in, it has access to the different applications, settings and other implemented features. According to the user's degree of disability, first time use of the settings screen may require help from a caregiver or a therapist.**

### *3.9.2. Facial recognition*

In order to simplify the customization of the system, we implemented a biometric identification module based on facial images. Once the user creates an account, we take images of the user face from multiple angles. All these images are processed offline and robust image descriptors are computed (local binary patterns (Ahonen et al., 2006)). At runtime we are able to automatically identify the user by using a nearest neighbor search based on the computed descriptor.

We have created a database with more than 50 users. Although the user identification algorithm scales according to the number of users in the system, for a database with more than 50 users it currently takes less than 200 ms to compute the descriptors and validate user identity.

### *3.9.3. Carousel Mode*

The carousel mode is a feature enabling users with reduced mobility, who are unable to perform certain gestures, to use the system, but with an even more reduced set of gestures. When enabled, the focus of the elements moves to the next GUI element after a fixed time interval, allowing the patient to use the system with only one gesture. The "next" and "previous" gestures are replaced by a looping carousel mode, letting the user perform the "select" gesture to confirm the highlighted option. The option to enable this interaction mode and the time interval setting to move the focus of the looping carousel can be configured in the user profile menu.

It is important to mention that this mode becomes critical when using head motion to interact with the system. If users can only perform a nod motion, they will still be able to use the system in combination with the carousel mode.

### *3.9.4. Size and shape of user interface components*

We have paid attention to every single detail of the application, making the size and the shape of user interface components scalable, based on the resolution of the digital tablet. In this way, users can easily find the main components of the GUI. In addition, every button and interaction element has the exact size required to make it comfortable for use by any of the human-machine interfacing devices.

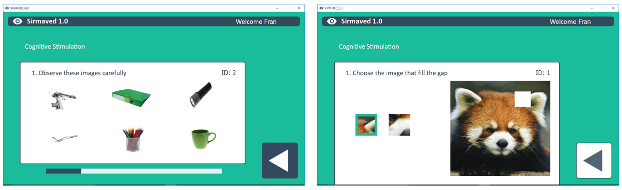
### *3.9.5. Text-to-speech*

We added a text-to-speech component to help people with visual problems, so they can still use the GUI and receive feedback on the option currently selected. In this case, we utilized Windows SDK to implement this feature in our system. Integration of this module into the proposed system is seamless and does not require any additional configuration from the user apart from enabling or disabling it. This action is usually carried out by the therapist or caregiver helping the patient during the initial rehabilitation sessions.

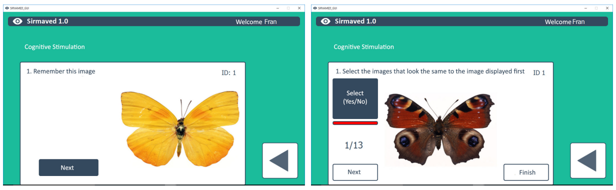
## 4. Application Scenarios

As stated before, brain damage may affect every area of an individual's functionality and the scope may vary from patient to patient.

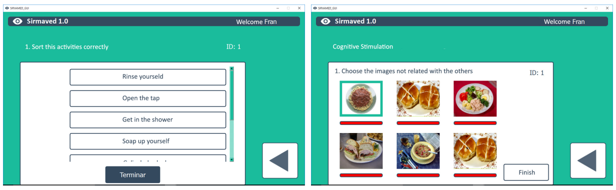
With this in mind, a number of apps were developed and integrated in the system, covering as many cognitive areas as possible. These apps were designed by a group of experts in the field with the aim of improving the cognitive capabilities of the patients. They are intended to be executed by any kind of patient regardless of their injury or physical disability. Each of these apps (from here on referred to as "activities") exercises a different part of the brain and leads to improvements in a specific ability. In addition, the therapist can create new custom activities for a given patient in order to motivate him or her and reduce the stress that may happen while performing rehabilitation. Additionally, in this regard, the patient does not know at



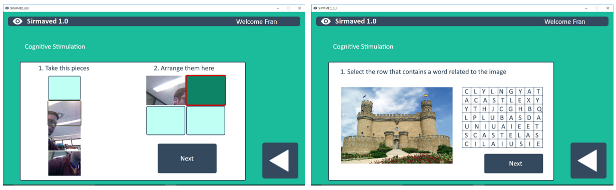
(a) Choose between six. (b) Fill the gap activity.



(c) Memory Carousel: first step. (d) Memory Carousel: second step.



(e) Temporal Sequence activity. (f) Multiple Choice activity.



(g) Puzzle activity. (h) Word Search activity.

**Fig. 7. Cognitive activities present in the system.**

any time whether or not he or she is successful when performing an activity, but the therapist does. Thus, it is the therapist who controls the patient's stress or excitement levels in order to manage their motivation. The caregiver will choose the most appropriate activities based on the patient's disabilities. The system is able to create a profile and to keep track of previous performed activities, so subsequently the patient (at home) is constrained to use a subset of the available activities.

We now describe the activities developed.

### *4.1. Choose between six*

As shown in Figure 7(a), six images are displayed for a short time frame in this activity. Once the time runs out, one of these images changes to a different one. The purpose of the activity is to detect which image has changed.

### *4.2. The missing gap*

The second activity is "The missing gap". In this case, a bigger image is shown with a missing section and two smaller images alongside. The patient must select which of the two smaller images completes the one as shown in Figure 7(b).

### *4.3. Memory Carousel*

This activity consists in two stages. In the first step, an image is shown to the patient, as displayed in Figure 7(c). When the therapist deems appropriate, the patient will continue to the next step. As seen in Figure 7(d), in the second step, a sequence of images is displayed, and the patient must select those that seem the same as the first image shown.

### *4.4. Temporal Sequence*

In this case, an unordered list of tasks is displayed. These tasks compose steps to complete a higher level task. The main purpose of this activity is to sort the tasks correctly in order to achieve the higher-level task. The main window of this activity can be seen in Figure 7(e).

### *4.5. Multiple Choice*

In this activity, up to six images are displayed as shown in Figure 7(f). Some of these images are not related to the others, so the purpose of this activity is to select all the unrelated images.

### *4.6. Puzzle*

In this activity, as shown in Figure 7(g), a picture is cropped, generating multiple images. At the beginning, these pieces are shuffled and displayed on the working area. The main objective of this activity is to select the pieces and to arrange them correctly.

### *4.7. Word Search*

The last activity integrated in the system is the Word Search. In this case, an image and a grid filled with letters are displayed side by side. One row of the grid contains a word related to the image. The patient browses the set of rows and must select the row with the word referring to the image, as shown in Figure 7(h).

## 5. User study

Having created a multimodal custom interaction system we wanted to evaluate it in an initial user study on people with different disabilities. The main aim of the study was to understand the usability/accessibility of the system and to get feedback from patients about how helpful the system was during the performance of some activities.

The user study was conducted in a hospital in collaboration with experts in acquired brain injury. A caregiver and a doctor participated in the study. For the user study, they recruited three patients suffering from acquired brain damaged and we also evaluated the system with three research lab members not involved in this project. Thus, six people participated in the user study.

Activities for the rehabilitation sessions were designed in collaboration with an occupational therapist and doctors from the Hospital of Seville. Each user took part in four sessions during four weeks, spending one hour per week. During the first session, the therapist helped the user to customize the interaction mode according to the user's disabilities. The system was trained using the sensors and the gestures that the therapist selected, based on the user's disabilities. Then, the user performed these gestures in front of the platform so it was able to learn these customized movements. During these sessions, users and patients were able to work on the developed activities and were able to solve them using some of the interaction modes. Finally, in the last session, users completed a satisfaction survey to evaluate the proposed system and the following aspects:

- Usability of the developed interfaces for human-robot interaction
- New technologies for cognitive rehabilitation
- User feedback on how autonomous the platform is and how much attention they received from the occupational therapist

For each of these aspects, several questions were proposed, so the user had to score each of the statements from 1-6. The satisfaction questionnaires can be found as a supplementary material.

After analyzing feedback from the users and observation notes taken during the development of the sessions, we found some interesting insights into the proposed platform. Further qualitative analysis revealed insights that fall into the previously listed categories.

Regarding the usability of the user interfaces, four out of six users found the experience was intuitive. Five out of six users also said that the custom interaction is motivating, making the use of these techniques for rehabilitation more attractive. Two users also reported they did not find the interface usable and, complained in general about the system sometimes failing to recognize user gestures.

In addition, three patients stated they would like to be able to use this robotic platform at home. As described by P2: *"I find this platform really motivating for doing rehabilitation at home."*. Finally, we wish to highlight that most users were satisfied with the system experience.

Since we have designed an adaptive platform, the proposed system has many different clinical uses, as we now describe. So far, we have evaluated the platform and developed activities for people with acquired brain damage. Within the patients and users that tested the platform, we found people with different degrees of disability. For example, a user with cerebral palsy and total paralysis was able to interact and carry out some exercises using the eye tracker interface. Another user with partial paralysis felt comfortable browsing interfaces by using hand gestures (short-range hand tracker). Therefore, based on the user study, we can conclude that rehabilitation (intellectual, memory and physical capacities) of people with acquired brain damage is one of the clinical uses that has been successfully evaluated. Moreover, we believe that the system can be used with other kinds of patients by developing new activities with the help of doctors and caregivers with expertise in other impairments. We also evaluated the proposed platform to help children with autism or cognitive learning disabilities to develop adequate communication skills (Gomez-Donoso et al., 2016).

Finally, it is worth mentioning that we are currently evaluating the platform for social integration of persons with motor disabilities. The main idea is that users can customize their way of interaction so as to use common computer programs, such as, email client, web browser and word processor. We plan to extend the Assistive Context-Aware Toolkit (ACAT) [3] to use our adaptive platform as an input.

## 6. Discussion and limitations

Being able to have partially autonomous assistive robotics platforms at home to help older adults and individuals with disabilities is becoming an urgent necessity for increasing quality of life. Moreover, not only does quality of life need to be improved, but families caring for relatives with different disabilities also need help. Finally, the authorities are also interested in reducing the monetary costs.

Although in the last 10 years, enormous progress has been made towards a ”robot era” where robotics platforms are a reality and can be deployed at home, most existing solutions still have low reliability and problems when dealing with real scenarios.

In our case, during the development of the platform, we found some limitations while trying to use multiple sensors for gesture recognition at the same time. Not only was there interference across sensors (Leap Motion and Kinect) but the user was also confused and it became more difficult to provide a natural interaction. For this reason, we decided that, based on the analysis of patient disability, the caregiver or therapist would decide which sensor is more suitable to provide a natural interface for user navigation during the rehabilitation process. The only interaction mode that can be used along with other ways of interaction are voice commands and touch. However, since some patients may also have cognitive problems, we found that a better experience was provided by using just a single interaction mode and avoiding complexities that would arise by simultaneously using different sensors.

We received feedback after carrying out initial trials of the system at the Hospital where the platform is currently being used. The robot navigation feature worked successfully in most cases; only when dealing with tight and cluttered scenarios did it present any cases of failure. Caregivers and patients found serious games very useful for performing rehabilitation therapies with patients with acquired brain damage. In particular, memory and puzzle games produced a positive feedback and response from both caregivers and patients. However, some specific interfaces presented problems while running some of the therapies. The close-up sensor sometimes had problems recognizing a patients gestures. This was caused by incomplete training of the gestures performed by the user. In these cases, the system did not react to the gestures, resulting in the users anxiety and distress. Another typical problem we found was

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[3] Assistive Context-Aware Toolkit (ACAT) is an open source platform developed at Intel Labs to enable people with motor neuron diseases and other disabilities to have full access to the capabilities and applications of their computers through very constrained interfaces suitable for their condition.

the customization of two very similar gestures, since when the input information (joints position) is very similar, our recognition system may classify wrongly.

Finally, we would like to highlight some of the innovative aspects and advantages of the proposed system:

- Enables multiple modes of interaction (gestures, hand poses/movement, voice, eye gaze, and touch) for persons with different disabilities, offering significant advantages over other systems.
- Enables customization of patients own gestures for each sensor, providing a natural and custom interaction experience with the system.
- Provides biometric identification (facial recognition), adapting the interaction (profiles) depending on the user disability level.
- Provides a flexible and modular workspace for the de- velopment of new applications oriented to novel therapies based on the different patients needs.
- Uses sensors and devices available on the market, and can therefore be modified, adapted and replicated easily at a reasonable cost depending on the type of patient, the disabilities and the therapies to be implemented.
- Provides a robotic mobile platform that can be used by patients at home.

## 7. Conclusions

In this paper, we propose an affordable system that addresses one of the main strands in social robotics, natural interaction. In this work, we also extensively discuss the necessity of adaptive multimodal communication interfaces for assistive robotics and reviewed existing solutions. We present a multimodal interaction system that has been successfully integrated in a mobile robotic platform for the interactive rehabilitation of disabled persons. Combining different sensors, we are able to provide custom gesture recognition for human-robot interaction. Moreover, an open framework is proposed which allows learning new gestures and creating profiles for each user according to their needs. Eye position, hand and body gesture and voice commands performed well on patients with acquired brain damage. Moreover, several applications have been developed using the proposed platform and have been evaluated with users with different disabilities. Positive feedback was obtained from users and caregivers who evaluated and tested the system during its development. The current version of the system is now being used by therapists at the Hospital of Seville where it helps to perform rehabilitation for patients with acquired brain damage. Moreover, some of the failures that have been discussed and the feedback obtained from the patients are being considered in order to improve the current system.

As future work, we plan to integrate the proposed system in other existing mobile robotics platforms such as the social robot Pepper. These types of robots are a perfect match for our system, making it the perfect companion at home and allowing natural and custom interaction for assistive robots. We are also exploring the possibility of integrating our adaptive interaction system with the Assistive Context-Aware Toolkit from Intel, allowing a more customized interaction for using computer software.

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