A Survey on Intelligent Wheelchair Prototypes and Simulators

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Abstract. Nowadays more than 700 million persons around the world have some kind of disability or handicap. During the last decades the elderly population in most of the European countries and across all the most civilized countries is also growing at an increasing pace. This phenomenon is receiving increasing attention from the scientific community, during the last years, and several solutions are being proposed in order to allow a more independent life to the people belonging to those groups. In this context Intelligent Wheelchairs (IW) are instruments that are a natural development of the scientific work that has been conducted to improve the traditional Wheelchair characteristics using health informatics, assistive robotics and human computer interface technologies. Some of the most important features of the IW are their navigation capabilities and automatic adaptation of their interface to the user. This paper presents the evolution and state of art concerning IWs prototypes and simulators and intelligent human-computer interfaces in the context of this devices. Our study enabled us to conclude that although several Intelligent Wheelchair prototypes are being developed in a large number of research projects, around the world, the adaptation of their user interface to the patient is an often neglected research topic. Thus, projects aiming at developing new concepts of Intelligent Wheelchairs are needed mainly using multimodal interfaces and wheelchair interfaces adapted to the user characteristics.

Keywords: Health Informatics, Human-Computer Interfaces, Simulation, Intelligent Wheelchairs, Wheelchair's Simulators.

1 Introduction

Nowadays more than 700 million persons around the world have some kind of disability or handicap [1] [5]. During the last decades the elderly population in most of the European countries and across all the most civilized countries is also growing at an increasing pace [2][3][4][5]. This phenomenon is receiving increasing attention from the scientific community, during the last years, and several solutions are being proposed in order to allow a more independent life to the people belonging to those groups.

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A wheelchair may be seen as a wheeled device that may be propelled either manually or using motors. Wheelchairs are instruments that were initially developed in order to give mobility to handicapped human beings. Currently the wheelchairs are seen as powerful resources to overcome severe limitations and disabilities resulting from several types of handicaps and illnesses. Moreover the concept of intelligent wheelchair (IW) is a natural development of the scientific work that has been conducted to improve the traditional Wheelchair characteristics. Some of the most important features of the IW are their navigation capabilities and automatic adaptation of their interface to the user.

This paper presents a brief description of the history of wheelchairs and their evolution and the state of art concerning IWs. Based on the state-of-the-art, a definition of intelligent wheelchair is presented. An overview of simulators used for testing and training in the context of wheelchairs and intelligent user interfaces and especially several adaptive interfaces applications is also presented.

2 Intelligent Wheelchairs

Although there are illustrations of wheelchairs in ancient Greek culture, it is considered that the first wheelchair is the one made for Phillip II of Spain in 1595. Then, in 1655, Stephen Farfler, a paraplegic watchmaker, built a self-propelling chair on a three wheel chassis [6]. The concept evolved from simple manually powered wheelchairs to electric wheelchairs and today new developments are presented in so called intelligent wheelchairs or “smart chairs” or even “robotic chairs” [7] [8].

The first intelligent wheelchairs were basically typical mobile robots to which seats, capable of accommodating user, were added [8]. Nowadays, science allows having intelligent wheelchairs, very similar in shape to traditional wheelchairs, with high manoeuvrability and navigational intelligence, with units that can be attached and/or removed and with high power independence.

In fact, definitions of Intelligent Wheelchair can be found at the works of Braga et al. [9] [4] and Simpson et al. [8]. Basically, an IW is a locomotion device used to assist a user having some kind of physical disability, where an artificial control system augments or replaces the user control [8]. The main objective is to reduce or eliminate the user's task of having to drive a motorized wheelchair. Typically, an IW is controlled by a computer, has a set of sensors and applies techniques derived from mobile robotics research in order to process the sensor information and generate the motors commands in an automatically way or with a shared control. The interface may consist of a conventional wheelchair joystick, voice based control, facial expressions or even gaze control, among others. The concept of IW is different from a conventional electric wheelchair, since in this latter case the user takes manual control over motor speed and direction via a joystick or other switch, without intervention by the wheelchair's control system. Thus, it is possible to enumerate the main characteristics of an IW [9] [10]:

- Interaction with the user using distinct types of devices such as joysticks, voice interaction, vision and other sensors based control like pressure sensors;

- Autonomous navigation with safety, flexibility and obstacle avoidance capabilities;
- Communication with others devices such as automatic doors and other wheelchairs.

3 Prototypes of Intelligent Wheelchairs

In the last years several prototypes of IW have been developed and many scientific work have been published [9] [4] in this area. Simpson [7] provides a comprehensive review of IW projects with several descriptions of intelligent wheelchairs from 1986 until 2004. Table 1 presents a list of some IW prototypes and describes their main characteristics.

Table 1. Intelligent Wheelchairs Prototypes

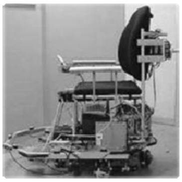
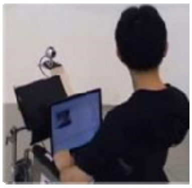
	**Madarasz** Autonomous wheelchair presented in 1986. It had a micro computer, a digital camera and an ultra-sound scanner.		**Omnidireccional IW** Hoyer and Holper presented in 1993 an omnidirectional IW.
	**Two legs' IW** In 1994 Wilman presented a hybrid wheelchair which was equipped with two extra legs.		**NavChair** The NavChair was presented in 1996. It was equipped with 12 ultrasonic sensors and an on board computer.
	**Tin Man I** Tin Man I, in 1995, presented 3 operation modes: driving with automatic obstacle avoiding; moving on a track; moving to a point.		**Tin Man II** Tin Man II, in 1998, presented more advanced characteristics: store travel information; return to starting point; follow walls; go through doors and recharge battery.
	**FRIEND's Project** Robot presented in 1999 which consists of a motorized wheelchair and a MANUS manipulator.		**LURCH** LURCH project (Let Unleashed Robots Crawl the House) started in 2007 aiming at developing an autonomous wheelchair.

Table 1. (*continued*)

	**RoboChair** In 2009 Robochair aimed to be an open framework for assistive applications, design modular and based in open standards for easy extension and low cost.		**VAHM** In 2010 the VAHM project presented a new prototype of an intelligent wheelchair with a deictic interface.
	**Intellwhells v1** In 2008, the 1st Intellwheels prototype was developed with high-level control through a multimodal interface (voice, head movements, joystick, keypad and simple facial expressions).		**Intellwheels v2** In 2012 a new prototype was developed at IntellWheels project with improved multimodal interface and ergonomics and automatic patient adaptation capabilities.

The first project of an autonomous wheelchair for physical handicapped was proposed by Madarasz [11] in 1986. It was planned as a wheelchair with a micro computer, a digital camera and an ultra-sound scanner with the objective of developing a vehicle that could move around in populated environments without human intervention. Hoyer and Holper [13] presented a modular control architecture for an Omni-directional wheelchair. The characteristics of NavChair like the capacity of following walls or obstacles deviation are described in [14] [15] [16]. Miller and Slak [17] [18] developed the system Tin Man I with three operation modes: one individual conducting a wheelchair with automatic obstacles deviation; moving throughout a track and moving to a point (x,y). This kind of chair evolved to Tin Man II which included advanced characteristics, such as, store travel information, return to the starting point, follow walls, pass through doors and recharge battery. Wellman [19] proposed a hybrid wheelchair which was equipped with two extra legs in addition to its four wheels, to allow it to climb stairs and to move on rough terrain. FRIEND is a robot for rehabilitation which consists of a motorized wheelchair and a MANUS manipulator [20] [21]. In this case, both the vehicle and the manipulator are controlled by voice commands. Some projects have a solution for quadriplegic people, where the recognition of facial expressions is used to guide the wheelchair [10] [22] [23]. In 2002, Pruski presented VAHM a user adapted intelligent wheelchair [24].

Satoh and Sakaue [25] presented an omni-directional stereo vision-based IW which detects both the potential hazards in a moving environment and the postures and gestures of a user using stereo omni-directional system, which is capable of acquiring omni-directional color image sequences and range data simultaneously in real time. In 2008 John Spletzer studied the performance of LIDAR based localization for docking an IW system [26] and, in 2009, Horn and Kreutner [27] showed how the odometric, ultrasound, and vision sensors are used in a complementary way in order to locate the wheelchair in a known environment. Currently there are several active international projects such as: RADHAR [28] that has the objective of developing a driving assistance system involving environment perception, driver perception and modelling and robot decision making, MAIA [29] project that aims the development of non-invasive prosthesis, the LURCH project [30] active until 2015, ARTY project [31] with the focusses in developing an intelligent paediatric wheelchair and a project from the University of Zaragoza [32] that is focused on mobile robot navigation and brain-computer interfaces.

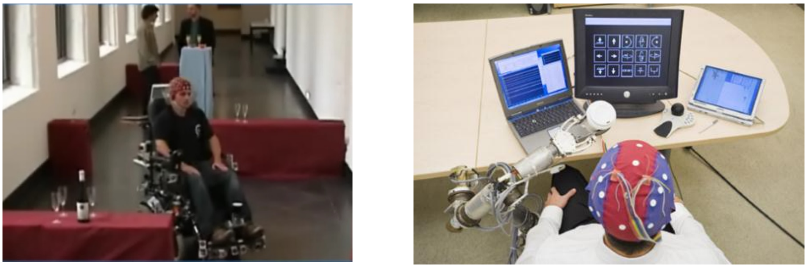


Fig. 1. Wheelchair and arm controlled by thoughts (Adapted from [33] [37])

In fact the research in IW has suffered a lot of developments in the last few years. Some IW prototypes are controlled with "thought" (Figure 1), this type of technology uses sensors that pick up electromagnetic waves of the brain [33] [34] [35] [36] [37].

Although there are several research projects in the area of intelligent wheelchairs and some business models that use new information technologies and robotics in support of a profound disability, there is a lack of wheelchairs with real capabilities of intelligent actions planning and independent navigation. Thus, one of the objectives of current research [4] [9] in this area is the integration into the intelligent wheelchair of ways to implement, in a semi-autonomous mode, commands of its users, in particular, using methods such as high-level command languages, navigation, semi-automatic, intelligent planning of actions and communication with other intelligent devices.

Another aspect that has been exposed to limited attention is the evaluation of the performance of the IW and long-term studies of the effects of using an IW or even studies using real patients and demanding constraints like low illumination, small areas or uneven floors. The CALL Center [38] [39] has a research group which studies which are the necessary skills to use a standard IW with young users. The CALL Center uses a standard power wheelchair equipped with bump sensors and line tracking sensors as an instructional tool for children learning to operate an IW [8] [39] [40]. Other interesting projects include the ENIGMA [41], an omnidirectional wheelchair from the University of Minho. Recently it is being used for the study of some applications of gestures commands. The Magic Wheelchair which is a gaze driven IW is part of the MagicKey Project from the Polytechnic Institute of Guarda [42]. In Coimbra, Portugal, a group of the Institute for Systems and Robotics developed a wheelchair steered with voice commands and which could be assisted by a reactive fuzzy logic controller [43].

There is also the project PalmIber [44] which is the continuation of Project PALMA (Support Platform Playful Mobility Augmentation) Ibero-American Program for Cooperation and Development (CYTED), which developed an IW prototype that has been tested at the Rehabilitation Center for Cerebral Palsy Calouste Gulbenkian in Lisbon. It has a multi-detector system of obstacles, composed of ultrasonic sensors; a set of interfaces for the user, which will allow controlling the vehicle through direct selection or selection by scanning and a programmable interface, allowing assigning different levels of complexity to the vehicle (speed, acceleration, and different ways to avoid obstacles, among others). However, only a few of these devices really had their performance tested with real users.

Most of the wheelchair projects presented did not include any reference to the user adaptation to the wheelchair or how to improve the IW interface based on the user interaction with the device. Therefore, an important project named IntellWheels [10] proposed an intelligent wheelchair with a multimodal interface. The interaction of the user with the IW and how an intelligent/adaptive interface can help and improve the user mobility was part of the study of this project [45][46][47][48][49][50][51].

4 Wheelchairs Simulators

The description of several simulators projects can be found in literature [52] [53]. The objectives of these simulators are concerned with the improvement of driving intelligent wheelchair and general manual/electric wheelchairs as can be observed in Table 2. The simulators have different objectives and fulfil important mission for testing the behaviour of humans and wheelchairs.

Table 2. Wheelchair's Simulators

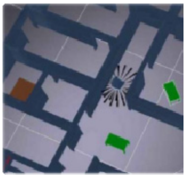
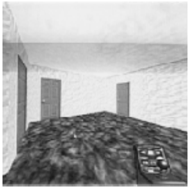
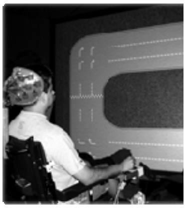
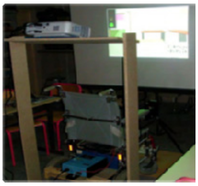
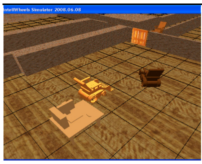
	**VAHM** The project VAHM of an intelligent wheelchair presents a simulator for testing the driving performance in 2000.		**Virtual Int.Wheelchair** In 2007 from the Mediterranean Univ. it was presented a simulator for evaluation of an intelligent wheelchair.
	**ITESM - CCM** In 2009, ITESM CCM presented an intelligent wheelchair and in 2012 a simulator was proposed for the user to get familiar with the controls.		**Powered Wheelchair Mobility Simulator** In 1993 from State University of New York a simulator of manual wheelchairs was proposed.
	**User Proficiency through Virtual Simulation** In 1994, a virtual structure prototyping system was proposed that allows navigation by a person using a powered wheelchair.		**Oregon Research Institute Simulator** In 1994 a simulator of an electric wheelchair using virtual reality was proposed by the Oregon Research Institute.

Table 2. (*continued*)

	**Simulator of Powered Wheelchair** In 1998 a wheelchair simulator was presented by the research team from National Rehabilitation Center for the Disabled in Japan.		**Royal Hospital for Neuro-disability vs University of East** In 2002 a join project used the role of virtual reality technology in the assessment and training of inexperienced powered wheelchair users.
	**Univ. of Strathclyde** In 2004, the University of Strathclyde presented a manual wheelchair controlled on a platform linked to a virtual reality screen.		**Virtual Env. Mobility Simulator** In 2005 a study was conducted in the virtual environment mobility simulator. Children could drive an electric wheelchair in different virtual environments.
	**Virtual Real. Wheelchair** In 2005, the Clarkson University presented a simulator that was also used by insure companies to give facilities for users to acquire wheelchairs.		**Univ. of Pittsburgh** In 2008 a study was published with tests performed by users with traumatic brain injury. A 2D virtual simulator was used to test the driving ability and measure the performance of alternative controls.
	**ISIDORE** In 2008, Toulon Univ. presented a simulation project to have a better evaluation of the user and more efficient information to therapists and doctors that prescribe wheelchairs.		**University of Florida** In 2009, a wheelchair simulator was proposed in the University of Florida.
	**McGill simulator** In 2011, McGill simulator was proposed using the Unreal Development kit and a comparison in real and virtual environments were conducted using an electric wheelchair.		**WheelSim** The WheelSim © Life Tool is a commercial simulator. The wheelchair can be commanded with a joystick, the keyboard or with the rollerball.
	**IntellWheels Simulator** In 2009 it was proposed the first simulator of an intelligent wheelchair with a multimodal interface.		**IntellSim** In 2012 Intellwheels project upgraded into a more realistic simulator based on USARSim and tested it with cerebral palsy patients.

The study of this kind of instrument has focused mostly in real electric wheelchairs. However, there are also some projects of intelligent wheelchairs that are concerned in presenting a simulator to perform tests [24]. There is also a work from the Mediterranean University (Virtual Intelligent Wheelchair) that presented a 3D intelligent wheelchair simulator where a wheelchair had an automated movement at a given trajectory [54]. The main constraint of this project was the lack of real users' participation. In 2009 the ITESM-CCM (*Ingeniería en Telecomunicaciones y Sistemas Electrónicos, Tecnológico de Monterrey, Campus Ciudad de México*) presented an intelligent wheelchair that could be commanded with voice commands and eye tracking [55]. In 2012 it was developed a simulator with the objective of enabling users to get familiar with the wheelchair's controls [56].

The Powered Wheelchair Mobility Simulator (PWMS) was a project developed in a center for assistive technology from USA and the objective was to develop an evaluation and training instrument for people with physical and cognitive constrains [57]. The performed tests allowed to conclude that the behaviour with the simulator has similar results as with the real wheelchair. The Virtual Electric Power Wheelchair Driving (VEPWD) was a project devoted to test speed control in outside/inside and with static/dynamic environments [58]. The Wheelchair User Proficiency through Virtual Simulation (WUPVS) project has the objective of provide a tool to overcome the limitation of users to real wheelchair training [59]. It is composed of an electric wheelchair linked to a workstation to simulate speed and orientation. The problem of providing disable people with accessibility to public buildings was one of the motivations for the development of this system. In fact, architects and conceivers could use this platform to test the environment accessibility. The Oregon Research Institute (ORI) has its focus in providing a wheelchair training simulator for children [60] [61]. Sound feedback has been integrated in the system in order to inform the impact when a collision occurs. The Assistive Technology Access Interfaces (ATAI) tested the capacity of basic driving simulator software to evaluate and train disabled children to command an electric wheelchair [62]. They tested two different groups of children one with and other without experience of driving wheelchairs. The results showed that after an initial training the group without experience could improve significantly the driving performances. The research institute on the National Rehabilitation Center for the Disabled in Japan proposed a Simulator of Powered Wheelchair (SPW) [63]. This system is composed with two computer screens and a mobile platform. The platform is connected with six actuators producing accelerations and decelerations similar to those in the real electric wheelchairs. The results demonstrated that users found similarities between real and virtual driving although the difficulties were higher when using the simulator. Another study that presented similar results about the differences between the experiments in virtual and real environments was evaluating and learning to drive an electric wheelchair from Royal Hospital for Neuro-disability and University of East [64]. From the University of Strathclyde a manual wheelchair being controlled on a platform linked to a virtual reality screen was proposed [65]. The users' motion is translated through an electromechanical platform to drive coordinates based on encoder takeoff at the wheels. From the University of Portsmouth, a research group worked on wheelchair obstacle avoidance by using virtual reality for elderly population [66]. The Virtual Environment Mobility Simulator (VEMS) provides a virtual environment where simple tasks are proposed to motivate the users [67]. The first conclusion of this project passes over the necessity of adaptation of the virtual environment to the user, since their incapacities are very diverse. The Virtual Reality Wheelchair (VRWC) is a simulator to test and train potential users of electric wheelchairs [68]. This simulator is also used for demonstrating to insure companies the ability in driving a wheelchair in order to obtain facilities for acquiring a wheelchair. From the University of Pittsburgh a Wheelchair Virtual Driving Environment was proposed in order to test the driving ability, the performance and to train users with brain injury with different controls such as the comparison between a standard motion sensing joystick and an experimental isometric joystick [69]. The ISIDORE (*Interface d'aide à la Simulation, à la DécisiOn et la REéducation*) from the Toulon University is a project that combines behavioral, visual and sound information to have a better evaluation of the user and more efficient information to therapists and doctors that prescribe the wheelchairs [70]. A wheelchair simulator was also proposed by a research team from the University of Florida. The simulator can simulate a manual and an electric wheelchair [71]. The McGill simulator was proposed using the Unreal Development kit (2011) and a comparison in real and virtual environments were conducted. The study allowed concluding that the performance in the simulator was similar to the real electric wheelchair; however in some tasks the driving in the simulator was more difficult [72]. A commercial wheelchair simulator is also available on the market: the WheelSim © Life Tool. This simulator aims at making easier the learning process of driving a wheelchair and also as a tool for diagnosis software or just a game to play [73]. The wheelchair can be commanded with a joystick, the keyboard or with a rollerball. The IntellWheels project developed two simulators were it was possible to drive an intelligent wheelchair with a multimodal interface. Several inputs

5 Conclusions and Discussion

The main focus of this paper was on the state of the art on Intelligent Wheelchairs and simulators as important instruments for testing and training. This survey may be quite useful for anyone researching on the areas of adapted user interfaces, intelligent wheelchair health applications for handicapped users or simulation of health devices. Although several Intelligent Wheelchair prototypes are being developed in several research projects, around the world, the adaptation of their user interface to the patient is an often neglected research topic. Typically the interface is rather rigid and adapted to a single user or user group. Thus, projects aiming at developing new concepts of Intelligent Wheelchairs are needed mainly using high-level commands, multimodal interfaces and wheelchair interfaces adapted to the user characteristics.

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