Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
2013

Brígida Mónica Teixeira de Faria

Classificação de Pacientes para Adaptação de Cadeira de Rodas Inteligente

Patient Classification for Intelligent Wheelchair Adaptation

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Patient Classification for Intelligent Wheelchair Adaptation

Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Informática, realizada sob a orientação científica do Doutor José Nuno Panelas Nunes Lau, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Thesis presented to the University of Aveiro for the fulfillment of the requirements in order to obtain the PhD degree in Computer Engineering under supervision of Prof. Dr. José Nuno Panelas Nunes Lau, Assistant Professor of the Department of Electronics, Telecommunications and Informatics of the University of Aveiro.

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“Colocar paixão, inovação e criatividade naquilo que fazemos, contribuindo para desenvolver ações e respostas, adequadas a cada problema ou situação de vida.”

Paixão - um dos valores da Associação do Porto de Paralisia Cerebral

o júri

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palavras-chave

classificação de pacientes, cadeira de rodas inteligente, descoberta de conhecimento, aprendizagem computacional, sistema de análise de dados, interface multimodal.

resumo

A importância e preocupação dedicadas à autonomia e independência das pessoas idosas e dos pacientes que sofrem de algum tipo de deficiência tem vindo a aumentar significativamente ao longo das últimas décadas. As cadeiras de rodas inteligentes (CRI) são tecnologias que podem ajudar este tipo de população a aumentar a sua autonomia, sendo atualmente uma área de investigação bastante ativa. Contudo, a adaptação das CRIs a pacientes específicos e a realização de experiências com utilizadores reais são assuntos de estudo ainda muito pouco aprofundados.

A cadeira de rodas inteligente, desenvolvida no âmbito do Projeto IntellWheels, é controlada a alto nível utilizando uma interface multimodal flexível, recorrendo a comandos de voz, expressões faciais, movimentos de cabeça e através de *joystick*. Este trabalho teve como finalidade a adaptação automática da CRI atendendo às características dos potenciais utilizadores.

Foi desenvolvida uma metodologia capaz de criar um modelo do utilizador. A investigação foi baseada num sistema de recolha de dados que permite obter e armazenar dados de voz, expressões faciais, movimentos de cabeça e do corpo dos pacientes. A utilização da CRI pode ser efetuada em diferentes situações em ambiente real e simulado e um jogo sério foi desenvolvido permitindo especificar um conjunto de tarefas a ser realizado pelos utilizadores. Os dados foram analisados recorrendo a métodos de extração de conhecimento, de modo a obter o modelo dos utilizadores. Usando os resultados obtidos pelo sistema de classificação, foi criada uma metodologia que permite selecionar a melhor interface e linguagem de comando da cadeira para cada utilizador.

A avaliação para validação da abordagem foi realizada no âmbito do Projeto FCT/RIPD/ADA/109636/2009 - "IntellWheels - Intelligent Wheelchair with Flexible Multimodal Interface". As experiências envolveram um vasto conjunto de indivíduos que sofrem de diversos níveis de deficiência, em estreita colaboração com a Escola Superior de Tecnologia de Saúde do Porto e a Associação do Porto de Paralisia Cerebral. Os dados recolhidos através das experiências de navegação na CRI foram acompanhados por questionários preenchidos pelos utilizadores. Estes dados foram analisados estatisticamente, a fim de provar a eficácia e usabilidade na adequação da interface da CRI ao utilizador. Os resultados mostraram, em ambiente simulado, um valor de usabilidade do sistema de 67, baseado na opinião de uma amostra de pacientes que apresentam os graus IV e V (os mais severos) de Paralisia Cerebral. Foi também demonstrado estatisticamente que a interface atribuída automaticamente pela ferramenta tem uma avaliação superior à sugerida pelos técnicos de Terapia Ocupacional, mostrando a possibilidade de atribuir automaticamente uma linguagem de comando adaptada a cada utilizador. Experiências realizadas com distintos modos de controlo revelaram a preferência dos utilizadores por um controlo compartilhado com um nível de ajuda associado ao nível de constrangimento do paciente. Em conclusão, este trabalho demonstra que é possível adaptar automaticamente uma CRI ao utilizador com claros benefícios a nível de usabilidade e segurança.

keywords

patient classification, intelligent wheelchair, knowledge discovery, machine learning, data analysis system, multimodal interface.

abstract

The importance and concern given to the autonomy and independence of elderly people and patients suffering from some kind of disability has been growing significantly in the last few decades. Intelligent wheelchairs (IW) are technologies that can increase the autonomy and independence of this kind of population and are nowadays a very active research area. However, the adaptations to users' specificities and experiments with real users are topics that lack deeper studies.

The intelligent wheelchair, developed in the context of the IntellWheels project, is controlled at a high-level through a flexible multimodal interface, using voice commands, facial expressions, head movements and joystick as its main input modalities. This work intended to develop a system enabling the automatic adaptation, to the user characteristics, of the previously developed intelligent wheelchair.

A methodology was created enabling the creation of a user model. The research was based on the development of a data gathering system, enabling the collection and storage of data from voice commands, facial expressions, head and body movements from several patients with distinct disabilities such as Cerebral Palsy. The wheelchair can be used in different situations in real and simulated environments and a serious game was developed where different tasks may be performed by users.

Data was analysed using knowledge discovery methods in order to create an automatic patient classification system. Based on the classification system, a methodology was developed enabling to select the best wheelchair interface and command language for each patient.

Evaluation was performed in the context of Project FCT/RIPD/ADA/109636/ 2009 – "IntellWheels – Intelligent Wheelchair with Flexible Multimodal Interface". Experiments were conducted, using a large set of patients suffering from severe physical constraints in close collaboration with Escola Superior de Tecnologia de Saúde do Porto and Associação do Porto de Paralisia Cerebral. The experiments using the intelligent wheelchair were followed by user questionnaires. The results were statistically analysed in order to prove the effectiveness and usability of the adaptation of the Intelligent Wheelchair multimodal interface to the user characteristics. The results obtained in a simulated environment showed a 67 score on the system usability scale based in the opinion of a sample of cerebral palsy patients with the most severe cases IV and V of the Gross Motor Function Scale. It was also statistically demonstrated that the data analysis system advised the use of an adapted interface with higher evaluation than the one suggested by the occupational therapists, showing the usefulness of defining a command language adapted to each user. Experiments conducted with distinct control modes revealed the users' preference for a shared control with an aid level taking into account the level of constraint of the patient. In conclusion, this work demonstrates that it is possible to adapt an intelligent wheelchair to the user with clear usability and safety benefits.

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Acronyms

AD – Alzheimer's Disease

ADWIN – ADaptive WINdowing

AI – Artificial Intelligence

ANN – Artificial Neural Network

API – Application Programming Interface

APPC – Associação do Porto de Paralisia Cerebral

AR – Auto-regressive

ARTY – Assistive Robot Transport for Youngsters

ATAI – Assistive Technology Access Interfaces

AUI – Adaptive User Interface

BCI – Brain Computer Interface

BIRCH – Balanced Iterative Reducing and Clustering using Hierarchies

C – Command

CFG – Context Free-Grammar

CL – Command Language

CM – Confusion Matrix

CMS – Common Mode Sense

CNS – Central Nervous System

CP – Cerebral Palsy

CRISP-DM – Cross-Industry Standard Process for Data Mining

CSUQ – Computer System Usability Questionnaire

CVFDT – Concept-adapting Very Fast Decision Trees

CYTED – Ibero-american program for Science, Technology and Development

DAS – Data Analysis System

DETI – Departamento de Electrónica, Telecomunicações e Informática

DM – Data Mining

DRL – Driven Right Leg

ECU – Environment Control Unit

EEG – Electroencephalogram

EOG – Electro-oculography

ESTSP – Escola Superior de Tecnologia da Saúde do Porto

FACS – Facial Action Coding System

FCT – Fundação para a Ciência e Tecnologia

FEUP – Faculdade de Engenharia da Universidade do Porto

FFT – Fast Fourier Transform

GMFCS – Gross Motor Function Classification System

GUI – Graphical User Interface

HMI – Human Machine Interface

I – Input

ICT – Information and Communication Technologies

ID – Input Device

IDAS – IntellWheels Data Analysis System

IEETA – Instituto de Engenharia Electrónica e Telemática de Aveiro

IMI – IntellWheels Multimodal Interface

INE – Instituto Nacional de Estatística

INESC-TEC – Instituto de Engenharia de Sistemas e Computadores Tecnologia e Ciência

IPP – Instituto Politécnico do Porto

ISIDORE – Interface d'aide à la Simulation à la Décision et la Reéducation

ITESM-CCM – Ingeniería en Telecomunicaciones y Sistemas Electrónicos, Tecnológico de Monterrey, Campus Ciudad de México

IW – Intelligent Wheelchair

IWP – IntellWheels Platform

KD – Knowledge Discovery

KDD – Knowledge Discovery in Databases

k-NN – k- Nearest Neighbour

LIACC – Laboratório de Inteligência Artificial e Ciência de Computadores da Universidade do Porto

LSD – Least Significant Difference

LURCH – Let Unleashed Robots Crawl the House

LWC – Light Weight Clustering

LWClass – Light Weight Classification

MAIA – Mental Augmentation through Determination of Intended Action

MCN – Modified Combinatorial Nomenclature

MRDS – Microsoft Robotics Developer Studio

ML – Machine Learning

MS – Multiple Sclerosis

ℕ – Natural Numbers

NIST – National Institute of Standard and Technology

OLIN – Online Information

ORI – Oregon Research Institute

PALMA – Plataforma de Apoio Lúdico à Mobilidade Aumentativa

POV – Point of View

PSD – Power Spectrum Density

PWMS – Powered Wheelchair Mobility Simulator

RADHAR – Robotic Adaptation to Humans Adapting to Robots

SAPI – Speech Application Programming Interface

SEMMA – Sample, Explore, Modify, Model and Access

SPW – Simulator of Powered Wheelchair

SUS – System Usability Scale

SVM – Support Vector Machines

TTS – Text to Speech

UA – Universidade de Aveiro

UDP/IP – User Datagram Protocol/Internet Protocol

UFFT – Ultra Fast Forest of Trees

UN – United Nations

UP – Universidade do Porto

USAR – Urban Search and Rescue

USARSim – Unified System for Automatic and Robot Simulation

USB – Universal Serial Bus

VAHM – Véhicule Autonome pour Handicapé Moteur

VEMS – Virtual Environment Mobility Simulator

VEPWD – Virtual Electric Power Wheelchair Driving

VFDT – Very Fast Decision Trees

VRWC – Virtual Reality Wheelchair

WIMP – Window, Icon, Menu, Pointer

WUPVS – Wheelchair User Proficiency through Virtual Simulation

Chapter 1

1. Introduction

Human-Machine interaction is currently a very active research topic. The analysis of the tasks for a human to perform, the information and technological requirements, the machine ergonomics and design are among the most interesting topics of study in this field. Systems that make the bridge between users and the processes to be controlled are another key point in this area. The challenges are even greater when studying the adaptation of technology used by individuals with disabilities in order to perform tasks that might otherwise be difficult or even impossible for them. Usability, accessibility and safety are among the concepts that must be considered when these instruments are being developed.

In the last decades the importance and concern given to the autonomy and independence of elderly people and patients suffering from disabilities has been growing steadly. In this context, intelligent wheelchairs (IW) are technologies that may increase the autonomy and independence of this kind of population and are nowadays a very active research area. On these devices Human-machine interaction is one of the most crucial aspects. This interaction is however an open research problem since each patient has distinct characteristics and is a completely different problem relatively to the other patients. Furthermore, adaptations of Intelligent Wheelchair to users' specificities and experiments of these devices with real users are topics that lack deeper studies.

The work described in this thesis tackles the problem of the adaptation of an intelligent wheelchair to specific users. In this context, concerns about usability, safety and accessibility are fundamental. The ultimate goal is to help individuals, that for some reason, do not have their total autonomy and independence and thus are unable to use electrical conventional wheelchairs, to be able to use an Intelligent Wheelchair after a brief user profiling and IW interface adaptation process.

1.1 Motivation

The main motivation of this work is the growing importance given to the autonomy and independence of elderly people and patients with some kind of disability. In fact, in 2006, the United Nations General Assembly adopted the Convention on the Rights of Persons with Disabilities [1] in which it is defended that "People with disabilities have the right to the measures to enable them to become as independent as possible" and "People with disabilities are entitled to medical treatment, psychological and functional treatment, including prostheses and orthoses, rehabilitation and social medical treatment…".

Another group that is growing and needs substantial attention is the elderly people. The number of elderly individuals and the growth of the elderly population are increasing in almost all developed countries [2] [3]. Hence, it is important to give an alternative that allows the elderly and the handicapped to be as autonomous as possible. Wheelchairs are one of the main tools to achieve this higher degree of autonomy. Moreover, the wheelchairs are evolving to Intelligent Wheelchairs with autonomous navigation and advanced user interface capabilities. These devices may further help elderly and people with disabilities like Alzheimer, Parkinson and Cerebral Palsy.

Intelligent Wheelchairs (IW) are becoming the solution to enable this higher degree of independence for wheelchair users. In addition, IW projects relevance is increasing, as more projects are launched every year, with distinct research focuses ranging from wheelchair hardware development to wheelchair shared control, from localization and navigation to new user interaction methodologies. Currently, one of the main research focuses is on the development of IWs capable of safe and autonomous navigation. Another research trend is on the development of IWs with higher levels of usability enabling high-level interaction between the wheelchair and its user. However, although automatic user configuration applications exist in other domains, the automatic configuration and parameterization of IWs to their users' characteristics is still an unexplored research subject.

1.2 Objectives and Thesis Statements

This project main objective is the development of a Data Analysis System (DAS) capable of analysing multimodal data, gathered from patients with distinct disabilities and use machine learning algorithms to perform automatic patient characteristics classification. To enable this global objective, the research performed comprises several other objectives:

- Development of a real data gathering system, enabling to collect real-time input information from patients with distinct disabilities and adaptation of a previously developed intelligent wheelchair, enabling the connection of the data gathering module;
- Execution of a complete data gathering process, collecting data from inputs/commands from patients with distinct disabilities (like different degrees of severity of patients with cerebral palsy) while using an intelligent wheelchair performing distinct tasks;

- Development of a multimodal interface that enables the IW to be commanded using a flexible command language and any type of combination of the available inputs (voice, head movements, joystick, facial expressions or thoughts);
- Implementation of a realistic simulator to enable experiments with a large number of patients in a controlled environment;
- Development of a data analysis system in order to obtain the best patient command language for driving the intelligent wheelchair;
- Execution of a series of experiments to validate the approach, testing the methodologies developed and all system modules with real patients with distinct disabilities.

The fulfilment of these objectives is essential to be able to test the main thesis statement: "Applying data analysis and machine learning methodologies within a flexible multimodal interface it is possible to automatically adapt an intelligent wheelchair to its user". Other statements in this thesis also arise, such as:

- User profiling may provide relevant information when automatically adapting an intelligent wheelchair to users with severe disabilities;
- It is possible to provide an automatically generated command language adapted to the user characteristics in order to drive an intelligent wheelchair;
- A data analysis system may provide a command language for driving an IW of equal or even better quality than the one provided by human specialists.

The support of ESTSP-IPP (Escola Superior de Tecnologia da Saúde do Porto – Instituto Politécnico do Porto) and APPC (Associação do Porto de Paralisia Cerebral) was crucial for developing the experimental part of the work using real patients. Also, the support of the proponent laboratories (IEETA at University of Aveiro and LIACC at the University of Porto) was decisive for integrating the developed work with the Intelligent Wheelchair prototype and simulator thus fully enabling to conduct this research. The final outcome of the project was a fully functional automatic wheelchair configuration methodology and tools that enables very fast and reliable utilization, by patients with distinct disabilities, of the wheelchair prototypes, previously developed by these research laboratories.

1.3 Contributions

The contributions of this work are broad mainly because the automatic adaptation of an intelligent wheelchair to a specific user (with severe constraints to drive it) is a recent paradigm. Several algorithms, tools and experiments were developed and applied to obtain effective results. A fully functional system that may be used by individuals, with severe limitations, to configure the interface they use when driving an electric wheelchair was proposed. The main contributions of this work are:

- Definition, design and implementation of the IntellWheels Multimodal Interface that enables to drive the IW with any combination of the available inputs [4] [5]. Although the concept of the IntellWheels multimodal interface had been published before [6], the current Multimodal Interface was a contribution of this work;
- Integration of new input devices for driving the IW, such as brain computer interface, virtual joystick and push button switch [7];
- Definition and development of an innovative User Profiling application with the specification of the protocol and tasks [8] [9] [10];
- Development of a new and more realistic simulator (*IntellSim*) and a realistic scenario where meaningful tests with real patients driving a simulated intelligent wheelchair can be performed [4] [9];
- Implementation of a shared control method where the user intentions are considered as inputs when driving the IW [11];
- Definition of a methodology enabling to create flexible command languages for driving the intelligent wheelchair [12];
- Definition and development of a Data Analysis System that provides a command language adapted to the user.

Besides these contributions, the work presented in this thesis also allowed the project divulgation through other international scientific publications and communications in the areas of Artificial Intelligence, Data Mining, Robotics and Assistive Technologies (Annex A). Furthermore, the IntellWheels project has been awarded with four prizes in the areas of Inclusion and Robotics demonstrating its recognition by several associations related with the project areas.

1.4 Structure of the Thesis

This thesis is organized in six chapters, in which the first one is composed by this introduction.

The second chapter presents the concept of Intelligent Wheelchair (IW) and its evolution together with the analysis of IW projects under development in distinct research laboratories. Since the thesis focus on the adaptation of the IW interface to its user characteristics, more attention is given to the adaptive/intelligent interface concept. Thus, a brief overview of research on this area is also presented. The chapter is concluded with a detailed presentation of the IntellWheels project that was developed at FEUP/LIACC, INESC-TEC and IEETA/UA. This project was the basis for the integration of the methodologies developed in this thesis.

The third chapter describes the standards and main phases in the Knowledge Discovery process, some recent applications, algorithms and implementations on this subject. This chapter contains several comparative results about available software and tools for Knowledge Discovery and Data Mining. It also presents applications of Knowledge Discovery and Data Mining algorithms and methodologies to problems on the health area.

The fourth chapter includes the description of the research methodologies developed for the extraction of users' profiles and the adaptation of the interface for driving the intelligent wheelchair. The multimodal interface concept is also explained together with the definition of the main concepts necessary to understand the developed methodologies. Thus, the concepts of input sequence, command and command language are explained. The new IntellWheels simulator *IntellSim* is also described with a previous contextualization of the methodologies for simulation. In order to facilitate the control of the IW for people with disabilities, the typical manual mode control was improved and a shared control method was developed. Finally, the description of the data gathering system, the data gathering process and the data analysis system are presented.

In the fifth chapter all the experimental work and the achieved results are presented. It is important to mention that all the methodologies were validated with empirical studies denoting the evolution and the path followed to obtain a scientific process for the adaptation of the intelligent wheelchair. The multimodal interface was studied both in real and in simulated environments. Tests about specific methods for controlling the wheelchair allowed obtaining promising conclusions in the aided control proposal. The experimental work also allowed refining the user profiling component and the data analysis system. Finally, the command language advisor results are presented and compared with the advices given by therapists in order to shown the usefulness of this approach.

Along this document brief conclusions are presented at the end of each section. Furthermore, the last chapter contains the main conclusions, contributions and originality of this work. Reflections about the limitations and perspectives for future work are finally presented.

Chapter 2

2. Intelligent Wheelchairs and Interfaces

Nowadays more than 650 million people around the world have some kind of disability or handicap [1] [13]. 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 [13]. 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.

A wheelchair may be seen as a wheeled device that may be propelled either manually or using motors [14]. 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 impairments 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 autonomous navigation capabilities and flexible human-machine interface such as automatic adaptation of the interface to the user.

This chapter 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. The low cost input devices that can be used to drive an intelligent wheelchair are also reviewed in this chapter. The last two topics presented in this chapter are concerned with the needed cares when producing multimodal interfaces with examples of projects that use this kind of interfaces and a general overview of the project IntellWheels and main achievements until the beginning of this thesis.

2.1 Intelligent Wheelchairs

2.1.1 Intelligent Wheelchair Concept

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 [14]. 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” [15] [16].

The first intelligent wheelchairs were basically typical mobile robots to which seats, capable of accommodating an user, were added [16]. 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. [17] [6] and Simpson et al. [16]. 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 [16]. 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.

It is possible to enumerate the main characteristics of an IW [18] [17]:

- 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 automatic doors and other wheelchairs.

2.1.2 Prototypes of Intelligent Wheelchairs

In the last years several prototypes of IW have been developed and many scientific work have been published [17] [6] in this area. Simpson [15] 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 some their characteristics. The first project of an autonomous wheelchair for physical handicapped was proposed by Madarasz [19] 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.

Madarasz 	Project of an autonomous wheelchair presented in 1986. Wheelchair with 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 Wellman presented a hybrid wheelchair which was equipped with two extra legs.	**NavChair** 	The NavChair was presented in 1996. It is equipped with 12 ultrasonic sensors and an onboard computer.
Tin Man I 	Tin Man I at 1995 presented three operation modes: - individual conducting a wheelchair with automatic obstacles deviation; - moving throughout a track; - moving to a point.	**Tin Man II** 	Tin Man II at 1998 presented more advanced characteristics: - store travel information; - return to the starting point; - follow walls; - through doors; - recharge battery.
FRIEND's Project 	Robot presented in 1999 which consists of a motorized wheelchair and a MANUS manipulator.	**LURCH** 	In 2007 started the LURCH (Let Unleashed Robots Crawl the House) project which aims at developing an autonomous wheelchair.
RoboChair 	In 2009 Robochair aims to be an open framework for future assistive applications [20]. 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.

ARTY		**Smart Driving Assistance**	
	In 2012 was published and presented the Assistive Robot Transport for Youngsters (ARTY). This is an intelligent paediatric wheelchair.		In 2012 was presented the results of the smart driving assistance from the University of Bremen [21].

Table 1: Intelligent Wheelchairs Prototypes.

Hoyer and Holper [22] 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 [23] [24] [25]. Miller and Slack [26] [27] 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 [28] 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 [29] [30]. 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 [18] [31] [32]. In 2002, Pruski presented VAHM a user adapted intelligent wheelchair [33].

Satoh and Sakaue [34] presented an omni-directional stereo vision-based IW which detects both the potential hazards in a moving environment and the postures and gestures of an 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 [35] and, in 2009, Horn and Kreutner [36] 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 [37] that has the objective of developing a driving assistance system involving environment perception, driver perception and modelling and robot decision making, MAIA [38] project that aims the development of non-invasive prosthesis, the LURCH project [39] active until 2015, ARTY project [40] with the focusses in developing an intelligent paediatric wheelchair and a project from the University of Zaragoza [41] that is focused on mobile robot navigation and brain-computer interfaces.

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 [42] [43] [44] [45] [46].

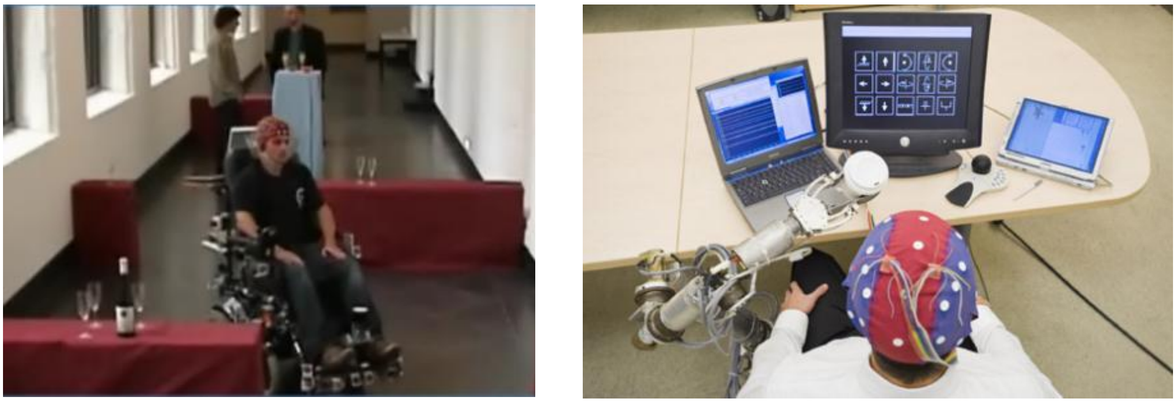


Figure 1: Wheelchair and arm controlled by thought (adapted from [42] [46]).

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 [6] [17] 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 [47] [48] 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 [16] [48] [49].

In Portugal there are also several interesting projects and research groups working on the concept of intelligent wheelchairs (Figure 2). The ENIGMA [50] is an omnidirectional wheelchair from the University of Minho. Recently it is being used for the study of some applications of gestures inputs. The Magic Wheelchair which is a gaze driven IW is part of the MagicKey Project from the Polytechnic Institute of Guarda [51]. In Coimbra, 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 [52].

Figure 2: Intelligent wheelchairs of Portuguese projects: Enigma, Magic Wheelchair and Wheelchair from the Institute for Systems and Robotics.

There is also the project PalmIber [53] which is the continuation of the Project PALMA (Support Platform Playful Mobility Augmentation) Ibero-American Program for Cooperation and Development (CYTED), which developed an IW prototype (Figure 3) 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.

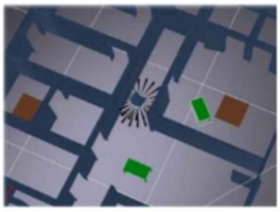
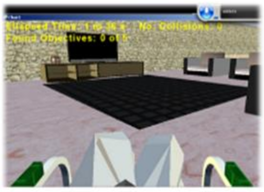
Figure 3: PalmIber wheelchair (adapted from [53]).

Most of the wheelchair projects presented did not include any reference to the user adaptation to the wheelchair nor how to improve the IW interface based on the user interaction with the device. Therefore, an important part of this study is the interaction of the users with the IW and how an intelligent/adaptive interface can help and improve the user mobility.

2.1.3 Wheelchairs Simulators

The description of several simulators projects can be found in literature [54] [55]. 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.

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 [33] (the first three cases in Table 2). 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 [56]. 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 [57]. In 2012 it was developed a simulator with the objective of enabling users to get familiar with the wheelchair's controls [58].

VAHM  The project VAHM of an intelligent wheelchair presents a simulator for testing the driving performance in 2000.	**Virtual Intelligent Wheelchair**  In 2007 from the Mediterranean University 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.
Wheelchair User Proficiency through Virtual Simulation  In 1994, a virtual structure prototyping system was proposed that allows navigation by a person using a power wheelchair.	**Simulator from Oregon Research Institute**  In 1994 a simulator of an electric wheelchair using virtual reality was proposed by the Oregon Research Institute.
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 publishes a work with results of the role of virtual reality technology in the assessment and training of inexperienced powered wheelchair users.

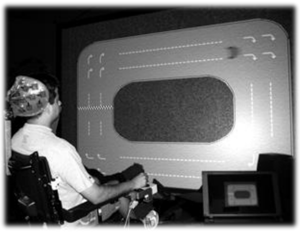
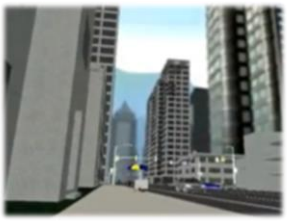
University of Strathclyde  In 2004, the University of Strathclyde presented a manual wheelchair controlled on a platform linked to a virtual reality screen.	**Virtual Environment Mobility Simulator**  In 2005 a study was conducted in the virtual environment mobility simulator. Children could drive an electric wheelchair in different virtual environments.
Virtual Reality Wheelchair  In 2005, the Clarkson University presented a simulator that was also used by insure companies to give facilities for users to acquire wheelchairs.	**University 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, the Toulon University a project was presented a simulation project to have a better evaluation of the user and more efficient information to therapists and doctors that prescribe the wheelchairs.	**University of Florida**  In 2009, a wheelchair simulator was proposed in the University of Florida.
McGill simulator  In 2011, the 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.

Table 2: Different wheelchair's simulators.

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 [59]. 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 [60]. 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 [61]. 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 [62] [63]. 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 [64]. 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) [65]. 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 [66]. From the University of Strathclyde a manual wheelchair being controlled on a platform linked to a virtual reality screen was proposed [67]. 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 [68].

The Virtual Environment Mobility Simulator (VEMS) provides a virtual environment where simple tasks are proposed to motivate the users [69]. 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 [70]. 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 [71].

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 [72]. 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 [73]. 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 [74].

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 [75]. The wheelchair can be commanded with a joystick, the keyboard or with a rollerball.

2.1.4 Input Devices

This section contains a summary of some low cost input devices that can be used in human computer interaction. Some recognition methods used to extract user intentions are also presented.

Firstly, the formal definitions of input and input device, used along this document, are next presented:

Definition 1: An **Input** (*I*) is a unitary action taken by the user that can be used to control the wheelchair.

Example 1: Saying “Go” and “Front” are two different inputs or “pushing the button number 3”, “leading the head to the right” and “blinking the right eye” are also examples of three more different inputs.

Definition 2: An **Input Device** (*ID*) is a peripheral that enables the user to interface with the IW providing a set of inputs.

Example 2: The microphone, wiimote, joystick and brain computer interface are some input devices available to drive the intelligent wheelchair.

The most popular mode of Human Machine Interaction (HMI) still depends on the keyboard and mouse. Although this pair of devices is extremely familiar, it sometimes limits the interaction flow between users and computers, namely in virtual reality systems and wearable computers [76]. The advances in signal processing, sensor technology and machine vision allow researchers to greatly expand the traditional user interfaces and devices.

A wide number of computer peripherals can be considered as input devices. Besides keyboard and mouse there are other input devices that can be used in HMI, such as microphone, video camera, joystick, tongue mouse, accelerometer, gyroscope, data gloves or even brain headsets.

There is a variety of recognition methods using different input devices [77]. In this section an overview of the most common techniques divided in video based systems, speech recognition, gesture recognition, thought recognition, sip and puff are presented.

2.1.4.1 Video Based Systems

Video based systems can be used to identify different types of human body motion. There are several applications related to video based recognizers, such as head movements, facial expressions [78] [79] or gesture recognition [80]. The facial expressions, gaze and position and orientation of the patients’ head to control the wheelchair are some of the examples used in several intelligent wheelchairs’ projects.

Facial Expression Analysis

Facial expressions can be defined as the facial modifications consequence of a person’s internal emotional states, intentions or social communications [81]. In 1978 [82], it was possible to verify an early attempt to automatically analysed facial expressions by tracking the motion of twenty identified spots on an image sequence. After that, much progress has been made to build computer systems that efficiently use this form of human communication [81].

Facial expression analysis is concerned with the development of computer systems that can automatically recognize facial motions and feature changes from visual information [81].

The Facial Action Coding System (FACS) is the most widely used method to measure facial movement. FACS defines 32 action units, each one representing a specific contraction or relaxation of one or more muscles of the face [83]. A number of intelligent wheelchair projects presented human-machine interfaces especially designed for quadriplegic individuals, by using facial expressions recognition as the main modality to drive the wheelchair [84]. A survey on several techniques for detecting facial expressions using Artificial Neural Networks, Hidden Markov Models and Support Vector Machines can be consulted in the paper of Gavankar et al. [85].

Eye Gaze Tracking

The first methods used for eye tracking benefit of Electro-oculography (EOG), which is a biological measurement technique used to determine the resting potential of the retina. An example of a system using this technique is Eagle Eyes [86], used in the Wheelesley wheelchair project. However, improvements in video recording and computer vision technology allowed the development of less invasive systems to track the user's eye motions [87]. Tall and Alapetite [88] presented a study about gaze-controlled driving using video-based systems to track the user’s eyes gaze orientation. In Portugal, a recent application of the MagicEye [89] also enables to drive an electric wheelchair.

Head Movements

Certain video based systems capture the orientation and position of the user’s head [18], which can be used as an input to represent specific desired outputs. This technique has been used in some wheelchair projects, namely at Osaka University [90]. In the WATSON wheelchair [91], a video system is used to detect the user’s gaze and face orientation.

Mouth Recognition

Mouth recognition is used to understand the users’ intention in order to obtain desired outputs. This method uses pattern recognition techniques to detect certain shapes of the mouth which act as inputs. Ju, Shin and Kim [92] proposed an IW interface using face and mouth recognition for severely disabled individuals. The direction of the wheelchair's movement changes according to the user's face inclination. By changing the shape of the mouth, the user can make the wheelchair move forward or stop.

2.1.4.2 Speech Recognition

Speech recognition is the process of decoding human spoken words to binary code comprehensible by the computer. The goal of speech recognition was to encourage independence since can be used to convert human speech signals into effective actions [93]. In many cases, speech is the only way individuals with disabilities can communicate. Youdin et al. [94] presented the first wheelchair system activated by voice. Equipped with an environmental control unit (ECU), users could control a number of devices, namely telephone, radio and page-turner, using voice commands. This approach received positive feedback from a group of individuals with cerebral palsy, who preferred the use of voice commands instead of breath control systems [93]. As the robustness of the available speech recognition systems was improved during the last years, the widespread availability of this low-cost technology was used in many other intelligent wheelchair projects such as NavChair, RobChair [95], Senario [96], TetraNauta and MIT Wheelchair [97].

Speech recognition can be used with reasonable success in many situations; however it still has some problems when the surrounding environment is noisy. Other situations include cases where the user’s voice does not match the training data, or when the user cannot achieve proper speaker adaptation. Sasou and Kojima [98] proposed noise robust speech recognition applied to a voice-driven wheelchair. Their approach consists of using an array of microphones installed on the wheelchair, unlike the common method of using a singular head microphone placed close to the user’s mouth. The achieved accuracy is very similar to the headset microphone method, and has the advantage of avoiding situations where the headset microphone position must be adjusted by the user. For hand disabled individuals, who are one of the major users of this wheelchair, this represents an interesting approach.

2.1.4.3 Gesture Recognition

Gesture recognition is the detection of a human gesture by a computing device. The goal of gesture recognition research is to develop systems which can identify specific human gestures and use them to send information for device control. Gesture recognition constitutes an alternative for disabled individuals to interact with computing devices. Hand and finger gestures can be recognized using sensors such as accelerometers and gyroscopes. Alternatively the computing device can be equipped with a camera so that specific software can recognize and interpret the gestures [99].

Data Gloves

A data glove is an interactive device, involving a glove worn on the hand, which facilitates tactile sensing and motion control in robotics and virtual reality. With the help of sensors it is possible to capture physical data such as the bending of fingers. Additionally, the glove's global position can be measured using magnetic or inertial tracking devices attached to the glove. The movements are interpreted by software, so any movement can be mapped to specific output actions. One example is the CyberGlove [100], a glove that captures the position and movement of fingers and wrist (Figure 4).

Figure 4: Cyberglove data glove (adapted from [100]).

It has up to 22 sensors, including three bend sensors for each finger, four abduction sensors, plus sensors measuring thumb crossover, palm arch, wrist flexion and wrist abduction. A recent technology, AcceleGlove [101], is an open-source data glove which can be programmed and adapted to specific applications, using a Java framework. DRive is a gesture recognition system that allows individuals with quadriplegia to control a car interface using a data glove. More information regarding this project is available at [102].

2.1.4.4 Sip and Puff

Sip-and-puff is another method used by hand disabled individuals to control devices such as wheelchairs, by sipping and puffing on a straw. It is mainly used by people who do not have the use of their hands. These mechanisms are often used by individuals with severe disabilities, such as quadriplegia. Sip-and-puff technology can also be used to control mouse movement in a simple and efficient way. Additionally, using sip-and-puff together with scanning software allows disabled users to use programs accessible by keyboard. Some wheelchairs use sip and puff technology to aid in the navigation [103].

2.1.4.5 Thought Recognition

The studies of the electrical signals produced by the brain are related to brain functions and also to the status of the full body [104]. By applying digital signal processing methods to the electroencephalogram (EEG) signals obtained from the brain activity it is possible, for example, to obtain patterns for diagnosis and treatment of brain disorders.

The beginning of research in terms of electrical signals emitted by the nerves of the muscles goes back to the nineteenth century with Carlo Matteuci and Emil Du Bois-Reymond [105]. Although the research in this area never stopped, the first experiments of EEG on humans belong to Hans Berger in 1929. He found the correlation between the mental activities and the changes in the EEG signals making possible the creation of new interactions. The devices that enable signals from the brain to direct some external activity are known as Brain-Computer Interfaces (BCI). The research developed in the seventies at the University of California Los Angeles and the related scientific papers mark the first appearance of the name Brain-Computer Interface in the literature [106] [107].

A brain-computer interface is a type of device which allows interaction between users and computer systems, through the recognition of brainwave activity. Normally, brain-computer interfaces are used in medical contexts, with the objectives of augmenting cognitive and sensory-motor functions.

The BCI can be classified in different categories [108]:

- Invasive/Non-Invasive - this classification refers to how the BCI is placed to obtain the brain activity. Invasive and partially-invasive BCIs require medical and surgical intervention, since they are implanted in the user's brain. Non-invasive BCIs do not require brain implants. However, non-invasive BCIs are less effective when compared to invasive BCIs, since the obtainable signal of brainwave activity is weaker.
- Dependent/Independent – if a BCI involves a certain level of motor control from the user it is then denominate a dependent BCI. On the other hand, if no motor control from the user is necessary it is called an independent BCI.
- Synchronous/Asynchronous – in Synchronous systems, the computer gives the user a cue to perform a certain mental action and then records the user’s EEG patterns in a fixed time-window. Asynchronous systems are determined by the user and operate by passively and continuously monitoring the user's EEG data and attempting to classify it in the moment.

The next sections, present a brief description of the biological foundations of neural activity, the brain rhythmic that can be acquired and the techniques for measuring the brain activity.

Neural Activity

The central nervous system (CNS) is the part of the nervous system that integrates the information which is received from all parts of the body and coordinates all the activity [104]. Basically the CNS is made of the brain and spinal cord. It is composed of axons, dendrites and cell bodies (Figure 5). An axon (or nerve fiber) is usually long and thin. Typically, it conducts electrical impulses away from the neuron's cell body. Dendrites are normally shorter and became thinner with distance and are branched projections of a neuron that act to conduct the electrochemical stimulation received from other neural cells to the cell body of the neuron from which the dendrites project [104]. Axons are different from dendrites in several features, including shape, length in which dendrites are restricted to a small region around the cell body while axons can be much longer, and function where dendrites usually receive signals while axons usually transmit them.

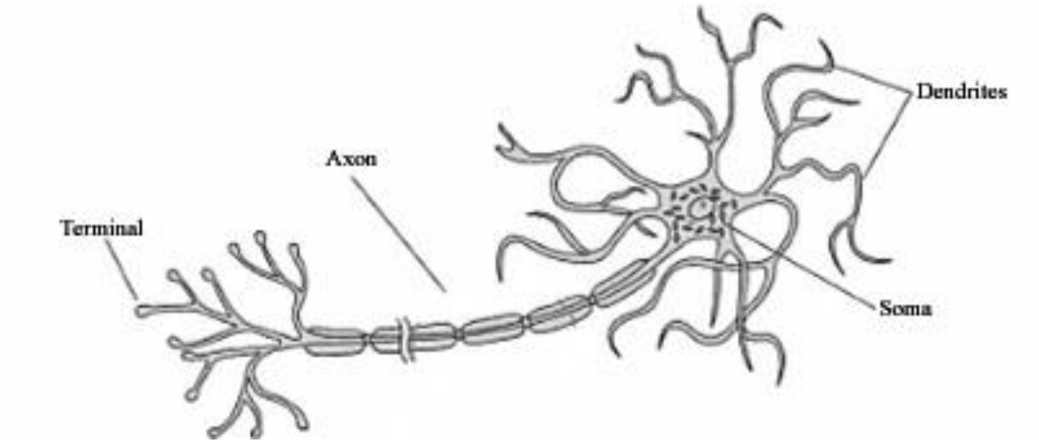


Figure 5: Neuron structure (adapted from [109]).

Axons make contact with other cells, usually other neurons but sometimes muscle or gland cells, at junctions called synapses. At a synapse, the membrane of the axon closely adjoins the membrane of the target cell, and special molecular structures serve to transmit electrical or electrochemical signals across the gap.

Brain and EEG Generation

The human brain is divided in three regions: the cerebral cortex, the cerebellum and the brainstem [109]. The cerebral cortex is also divided in four parts, such as the frontal, the parietal, the temporal and the occipital lobes. The frontal lobe has the function of thinking, planning, solving problems and executes functions and motor movements; the parietal lobe is responsible for seeing spatial relations between objects; the temporal lobe is dedicated to the language and auditory processing and long term memory and emotion; the occipital lobe is responsible of seeing, visual-perception and processing visual input. The cerebellum is intimate linked to control all the motor movements. Finally, the brainstem is located at the posterior part of the brain. Brainstem also plays an important role in the regulation of cardiac and respiratory function. The functions associated with this part of the brain provide the nerve connections of the motor and sensory systems from the main part of the brain and the rest of the body and it also regulates the central nervous system. Figure 6 shows the division of the human brain.

A human brain has two hemispheres that are similar however very different in terms of functions. In most individuals the left hemisphere is more connected to mathematical, logical and language behaviours and the right hemisphere typically is related with spatial skills, music and imagery.

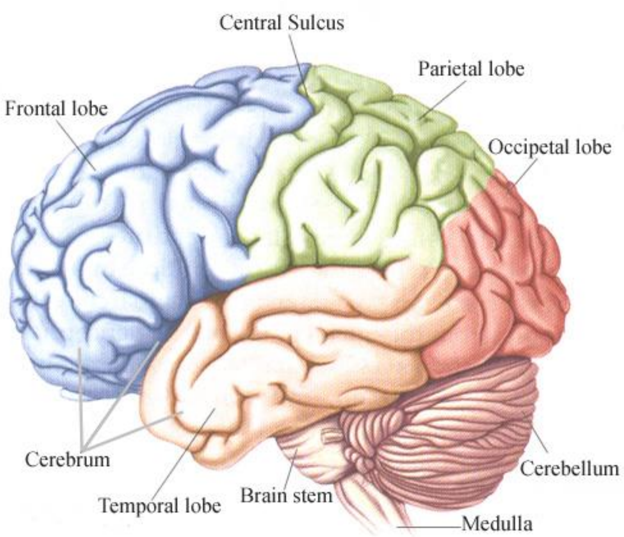


Figure 6: Regions of the human brain (adapted from [110]).

The grey matter is distributed at the surface of the cerebral cortex and of the cerebellum, as well as in the depths of the cerebrum, cerebellar, brainstem and spinal grey matter [111]. This grey matter contains the neuron cell bodies, dendrites and axons.

In the human brain each nerve is connected to thousands of other nerves [104]. An EEG signal is the measurements of the activity that flows during the synaptic excitations of the dendrites of many neurons in the brain [104]. When the brain neurons are activated synaptic flow is produced in the dendrites. This current generates a magnetic field that can be measured by an electromyogram and a secondary electrical field over the scalp measured by EEG systems [104].

Since the human head is composed of different layers such as scalp, skull, brain and other kind of thin layers, the signal measured at the scalp is attenuated. For that reason and because of the internal, external and system noises, recording electric measures using the scalp electrodes is only viable in areas of large populations of bouncing neurons. In addition, it is necessary to amplify these signals in order to display the information [112].

EEG frequency and Brain Rhythms

The EEG signals allow observing the detection of brain rhythms. These rhythms change along the human states (such as sleep or being awake) and with the age. It is possible to distinguish five major brain waves by their frequency ranges. The frequency bands are delta (δ), theta (θ), alpha (α), beta (β) and gamma (γ) [113]. Table 3 has the band, frequency and possible state of the individual [112].

Brain Waves	Frequency Ranges (Hz)	Possible Human State
Delta	< 4	Manifests in babies and decreases with aging. Can be observed in adults sleeping.
Theta	4 – 7	Can be observed in young and older children and in normal adults in meditative and sleepy states.
Alpha	8 – 11	Primarily reflect visual processing in the occipital brain region. May be associated to the memory brain function and mental effort. Increasing mental effort causes a suppression of alpha activity.
Beta	12 – 29	Associated with motor activities. The waves are characterized by their symmetrical distribution when there is no motor activity. In case of activity this distribution changes.
Gamma	30 – 100	Waves are related to several motor functions or perceptions in the brain activity of a healthy adult. There are also evidences to attribute visual and auditory stimuli to gamma activity.

Table 3: Brain waves, frequency ranges and human state.

The EEG signals can be recorded from electrodes that are placed on the scalp of the human brain. In order to ensure the reliability of the studies in terms of reproducibility over time and subjects, the International 10-20 system was implemented. This system is explained in the next section.

International 10-20 System

The system is based on the association between the location of an electrode and the primary area of cerebral cortex. The “10” and “20” numbers refer to the distances between adjacent electrodes (Figure 7). In fact, the electrodes are placed either 10% or 20% of the total front-back or right-left distance of the skull [114] [115].

The letters and numbers correspond to the localization of the sensors and are inspired in the respective lobe and hemisphere: the letter A represents the ear lobe, C the central region, F frontal, T temporal and P parietal and O occipital lobes [112]. The “z” (zero) refers to an electrode placed on the middle. Even numbers (2,4,6,8) refer to electrode positions on the right hemisphere, whereas odd numbers (1,3,5,7) refer to those on the left hemisphere.

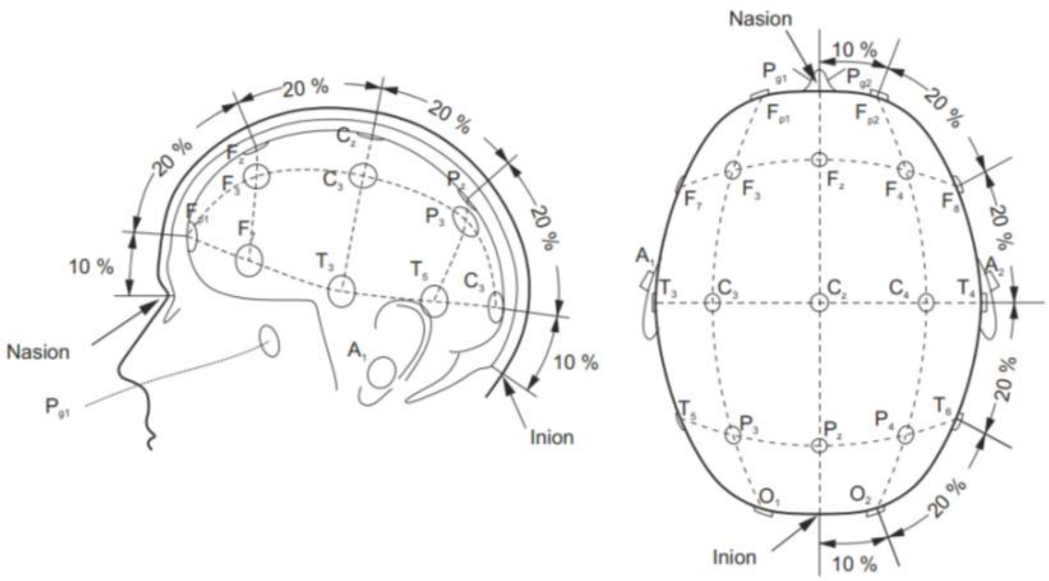


Figure 7: International 10-20 System (adapted from [112]).

The Nasion and the Inion are the marks for positioning the EEG electrodes. The Nasion is the point between the forehead and the nose. The Inion is the lowest point of the skull from the back of the head and is normally indicated by the most prominent projection of the occipital bone in the back of the scalp.

It is possible to introduce more electrodes using the spaces between the existing 10-20 systems. Normally this new systems are denominated as Modified Combinatorial Nomenclature (MCN) [115]. The introduction of extra letters allows the identification of extra electrode locations.

Brain Computer Interfaces in IW

The idea of integrating brain computer interfaces in intelligent wheelchairs has already been presented in the literature and the birth of the brain controlled wheelchair was presented by Carlson et al. [42]. The wheelchair prototype developed by the LURCH project [39] uses a non-invasive BCI that allows the user to drive the wheelchair. Recently this project presented several other options such as touch-screen, miographic interface and the classical joystick for driving the wheelchair [116].

By using a headset equipped with a number of electrodes, the user can train thought patterns that will be associated to a certain output action. In spite of being in a premature state of development, this technology might be interesting, namely for severely disabled individuals.

The MAIA project is a European project aiming at the development of an electroencephalography-based brain-computer interface for controlling an autonomous wheelchair [38]. The wheelchair control has automatic obstacle avoidance and is also capable of following walls. The user can control the wheelchair movement giving commands such as "go back" or “go right”. Blatt et al. [117] propose a slightly different approach for a user to drive an intelligent wheelchair, using a BCI. Instead of performing high-level commands, the user must continuously drive the wheelchair. Another project under development at the National University of Singapore consists of an autonomous wheelchair controlled through a P300-based BCI [45]. The wheelchair movements are limited to predefined paths. The user selects a destination, and the wheelchair automatically calculates the trajectory to the desired place. If an unexpected situation occurs, the wheelchair stops and waits for further commands.

Unfortunately, some problems may arise while trying to use a BCI. Brain activity varies greatly from individual to individual, and a person's brain activity also changes substantially over time [118]. These obstacles make it difficult to develop systems that can easily understand the user intentions, especially for long periods of time. Also, several weeks of training are necessary before a user can correctly use a BCI to control a specific device [118].

2.2 Adaptive/Intelligent User Interfaces

2.2.1 User Interfaces

The interface between a human and a computer is called a user interface and is a very important part of any computerized system. Moreover an adaptive user interface [119] is a software entity that improves its ability to interact with a user by constructing a user model based on the experience with that user. The emerging area of adaptive and intelligent user interfaces has been exploring applications in which these paradigms are useful and facilitate the human machine communication [120]. In fact, if an intelligent user interface has a model of the user then this user model can be used to automatically adapt the interface. Moreover, adaptive user interfaces may use machine learning to improve the interaction with individuals in order to have the users reach their goals more easily, faster and with a higher level of satisfaction. It is also essential for an adaptive interface to obtain knowledge included in four distinct domains: knowledge of the user; knowledge of the interaction (modalities of interaction and dialogue management); knowledge of the task/domain; and knowledge of the system characteristics [121].

2.2.2 Adaptive Interfaces

Ross [120] presented a comprehensive classification of adaptive/intelligent interfaces. His classification contains three main classes:

- The first class involves the addition of adaptation to an existing direct manipulation interface. Adding extra interface objects in order to hold the predicted future commands or alternatively designing an interface with multiple commands;

- The second class is composed by interfaces acting as an intermediary between the user and the direct manipulation interface by filtering information or generating suggested data values;
- The third class is composed by agent interfaces, in which autonomous agents [122] [123] can provide pro-active support to the user and typically can make suggestions and give advice.

It is also mentioned that many intelligent interfaces can be viewed as adaptive user interface, because they change their behaviour to adapt to an individual or assignment [120]. Another taxonomy defended by Langley [124] for adaptive user interfaces (AUI) is based on separating them into two groups: Informative Interfaces and Generative Interfaces. The first class selects information for the user and presents the items he will find interesting or practical. The second process tries to generate useful knowledge structures like spreadsheets, document preparation or drawing packages.

Programming by Demonstration is another class of adaptive interfaces presented in the literature [125] [120]. This class is distinct from the previous since generative interfaces produce data values, but programming by demonstration systems produce commands with arguments. Table 4 presents several applications divided by the above mentioned taxonomy.

AUI Class	Applications	Description
Informative Interfaces	WiseWire (1995) [126]	Recommendation of news articles and web pages to its customers.
	Syskill & Weber Pazzani, Muramatsu and Billsus (1996) [127]	Recommendation of web pages to users.
	VoxelBar (2008) [128]	An informative interface for volume visualization.
	FilmFinder (2009) [129]	System that constructs a simple user profile and suggests films that are similar to the one viewed before but are not yet seen.
Generative Interfaces	Clavier (1994) [130]	An advisor system that recommends loads and layouts for aircraft parts to be cured in an autoclave.
	Hermens & Schlimber (1994) [131]	An adaptive system for filling out repetitive forms.
	Phrasier (1999) [132]	An interactive system for browsing, querying documents within digital library.

	GPS (2009) [119]	Almost every GPS systems has a generative interface.
Programming by Demonstration	Cypher (1993) [125]	Contains a representative sample of work on programming by demonstration.
	Calinon (2009) [133]	Robot programming by demonstration.

Table 4: Adaptive user interfaces taxonomy.

2.2.3 Adaptive Interfaces Applications in IW

The area of intelligent interfaces is an emergent area with only a few studies concerning adaptive/intelligent interfaces applied to intelligent wheelchairs. This way, the main scientific progress in the area of adaptive interfaces and related concepts applied to intelligent wheelchairs are described next.

In the NavChair [25] a method for automatically allocating control between the wheelchair and its operator was applied. The project evaluated the performance of the NavChairs' automatic adaptation mechanism through an experiment in which subjects used voice control to drive the NavChair through a navigation task requiring several transitions between operating modes.

In a different but interesting way Tan [134] proposed an intelligent chair in which it is possible to identify the posture of the user by analysing and training the computer to recognise pressure patterns associated with different seating postures. It is also described that in a recent future the smart chair will interface with smart rooms, smart desks and smart clothes to form an interactive electronic environment that is friendly and useful to the user.

Rao [135] presented an intelligent chair focusing in the vision-based human interaction interface, the suite of sensors on the chair, the software architecture and the control algorithms used to control the chair. Later, Parikh et al. [136] demonstrated some usability results for the smart chair.

The main goal of TetraNauta project [137] was to design a non-expensive automatic driving system to help wheelchair users to move with minimum effort. So the design of an adaptive mobile user interface was presented in the context of this project.

Pruski et al. [33] proposed a multi-agent based control to ensure the best choice of control in a given environment and according to the user preferences in the context of VAHM.

Rousan and Assaleh [138] presented a wheelchair which can be moved using one of the three techniques integrated in the wheelchair: a joystick, direction buttons or voice. For recognition of the voice commands, the system uses wavelets and neural networks for feature extraction and classification.

Others concepts concerning adaptive interfaces that must be considered are the usability, accessibility and safety. In fact, almost every investigation on intelligent wheelchairs reports studies of usability and accessibility. However, these studies are typically superficial without the use of any validated scale of usability.

2.2.4 Adaptive Interfaces Characteristics

2.2.4.1 Usability

The term usability has different lines that accomplish the general definition. Dumas and Redish [139] state that the definition should be based on four main lines: usability means focusing in users; people use products to be productive; users try to complete tasks and users decide when a product is easy to use. In conclusion, usability is the scale to which the design of a particular user interface takes into account the human psychology and physiology and makes the process of using the system effective, efficient and satisfying [140]. Paraphrasing, usability is also related with the functionalities of the product (in this case the wheelchair) and the process to design it.

The usability of IWs has also been studied but with very few details. Reis et al. [6] performed a simple test of usability of the IW prototype - IntellWheels. However, this perspective was not fully explored and a more concrete study should be performed, since the main innovation in the IntellWheels interface is the multimodal interaction. This multimodality brings several improvements to the interface. The output control is achieved by the combination of several inputs, only being limited by the total number of inputs. Since the interaction between the inputs can differ depending on the environment, this multimodality achieves greater flexibility since when any input become less recognizable, it may be compensated by another.

2.2.4.2 Accessibility

The term accessibility is normally used to describe the degree to which a product, device, service or environment is accessible to individuals [141]. The term accessibility is often used to centre on handicapped people and their right to access everything and everyone, in most of the cases through use of assistive technology. This is about making things accessible to all people.

This reveals the importance of the IW as a mean to give everyone a way of moving in an autonomous manner and have an independent life, independently of their degree of incapacity.

2.2.4.3 Safety

The safety of an interface is fundamental. In the context of an Intelligent Wheelchair this safety concern is even more important and consists in a crucial aspect of the IW project.

The safety of users is fundamental and as Simpson [15] claims there is a lack of experimental results with real users of intelligent wheelchairs except the effort made by CALL-Centre [47]. To suppress this kind of problem, some research projects have proposed the use of simulators in order to conduct some of the experiments [142], hence providing a safe virtual environment. The knowledge gathered in simulation is then applied to avoid possible damages to the users in the real IW.

Safety is one of the key objectives of any Intelligent Wheelchair interface. The IntellWheels project aims at recognizing the main problems faced by users when manoeuvring an intelligent wheelchair and at developing solutions to overcome these problems. An important aspect of this work is to classify the users and automatically provide the best interface for a specific individual in order to maximize its safety using the IW.

2.3 Multimodal Interfaces

Several definitions of Multimodal Interfaces can be found in the literature as in [143]. Oviatt [144] defended that a “Multimodal interfaces process two or more combined user input modes, such as speech, pen, touch, manual gestures and gaze, in a coordinated fashion with multimedia system output”. The interaction style provided by multimodal interfaces allows users to have a higher flexibility to combine modalities of inputs, or to switch from one input to another that may be better suited for a particular task or setting. For disabled individuals this interface paradigm can be a benefit.

In the last years, improvements have been made in the hardware and software necessary to support the technologies associated to multimodal systems, allowing the development of more reliable and general multimodal systems [144]. The applications of multimodal systems is wide, ranging from virtual reality systems used for simulation and training, to biometric identification systems and also medical and educational purposes [144]. In more recent years, recreational technology such as video game systems and smartphones has also been adopting the multimodal paradigm. However, as opposed to the WIMP (Window, Icon, Menu, Pointer) graphical user interfaces, in which the input is generally deterministic, the results of multimodal interfaces recognizers have an associated degree of uncertainty, due to the probabilistic nature of such recognizers [145]. Also, multimodal systems depend on synchronized parallel processing, since multiple recognizers are needed to interpret multimodal input. Additionally, the time sensitivity of these types of systems is crucial to distinguish between parallel or in sequence multimodal commands [145].

2.3.1 Design Principles for Multimodal Systems

Classical design principles for human computer interfaces recommend leading iterative evaluations at different stages in the design process [146]. While evaluating the design of multimodal interfaces, the input and output characteristics should be considered and the influences of these two components on each other should be tested [146]. The definition of modality reflects the components of input and output:

Definition 3: A **Modality** (*M*) is a path of communication employed by the user to carry input and output.

Example 3: Voice, Head movements and Hand movements in the joystick are examples of distinct modalities.

During the past two decades, design principles and guidelines that should be followed to achieve more effective and robust multimodal interfaces have been proposed based on empirical research [144]. Larson et al. [147] proposed a list of design principles for multimodal interface systems. The multimodal systems should be broad and easy to adapt to different users and contexts. The privacy and security should be preserved; in fact, the personal information should not be public. Another principle is that the modalities should integrate in a compatible manner with the users' preferences and capabilities.

Generally synergy, robustness, modularity, customizability and consistency are the most important features multimodal systems should have. Other two important concepts regarding multimodal interfaces design are the fusion of multimodal inputs, and the multimodal fission to generate appropriate output messages to the user, based on user preferences, profile and context [148].

Besides the characteristics that were already discussed about usability, accessibility safety, design and evaluation of the interface, there is also an important issue that a developer should be focussed related to the concept of multimodal interfaces which is the model of the system use [143]. The main objective is to present a model that system designers should follow in order to develop usable new multimodal applications. The AMITUDE [143] is proposed as model of system use. In, fact it is a generic model which presents the aspects involved when someone uses a system. The meaning of the acronyms is a reorder of the bold uppercase letters in the sentence: "**U**ser who **I**nteracts with an **A**pplication in an **E**nvironment of use in order to do some **T**ask or other activity by using a certain interaction **D**evices and exchanging information with the system in certain input/output **M**odalities." [143].

2.3.2 Multimodal Interfaces Projects

Several projects were developed involving the presentation of multimodal interfaces. A classic example of a multimodal interface is the Media Room demonstration system. This system, presented by Bolt [149], constitutes one of the first attempts to combine speech and gesture recognition. Users could create objects on a map, and define their attributes, such as colour and size. Additionally, by saying "Put that there", users could move objects positions on the map, firstly by pointing to the specific object, followed by pointing to the desired destination.

MATCHKiosk is a multimodal interactive city guide allowing users to access information of New York City subways and restaurants. Using pen input, users can interact with the interface by drawing on the display. It also allows synchronous combination of inputs, using both speech and pen input to ask detailed information to the system. The information is presented graphically, synchronized with a text-to-speech synthesizer [150].

Another widely known map-based application, QuickSet [151], also makes use of speech and gesture input. This military-training system allows users to draw out with a pen at a given position on the map, using predefined symbols to create new platoons. As an alternative, users can use voice commands to create such platoons, being also able to specify the new position for the platoon vocally. Additionally, users can also express the intent of creating a new platoon using voice recognition, while pointing with the pen the desired location on the map [151].

An example of an assistive multimodal interface intended for persons with hands and arm disabilities is ICANDO (Intellectual Computer AssistaNt for Disabled Operators). This multimodal interface has a speech recognizer for English, Russian and French. In combination with a head tracking module, the system enables hands-free interaction with a graphical user interface in a number of tasks, namely manipulation of graphical and text documents [152].

OpenInterface [153] is an interesting project which goal is the development of an open source platform to enable rapid prototyping development of multimodal interactive systems, based on the reutilization of components developed by several research labs.

Another interesting project that involves multimodal interfaces is the Living Usability Lab [154] [155]. This project intends to produce the most natural and appropriate interfaces and technological solutions that should facilitate the daily lives of the elderly or those with disabilities, combat isolation and info-exclusion, increasing their ability to work, autonomy and improving their health and wellbeing.

2.4 IntellWheels Project

This section presents a brief overview of the Intelligent Wheelchair project that was developed at the Faculty of Engineering of University of Porto (FEUP) in collaboration with INESC TEC and the University of Aveiro and the first results of this project that have been published before the start of the work described in this thesis.

The main objective of the IntellWheels Project is to develop an intelligent wheelchair platform that may be easily adapted to any commercial electric wheelchair and aid any person with special mobility needs [17] [156].

Initially, an evaluation of distinct motorized commercial wheelchair platforms was carried out and a first prototype was developed in order to test the concept. The first prototype was focused on the development of the modules that provide the interface with the motorized wheelchair electronics using a portable computer and other sensors. Several different modules have been developed in order to allow different ways of conveying commands to the IW. These include, for example, manual modules (user inputs) such as joystick control with USB, control with head movements and using video based system for acquiring information about facial expressions [157].

The project research team considered the difficulty that some patients have to control a wheelchair through the traditional command mode. Therefore, new ways of interaction between the wheelchair and the user have been integrated, creating a system of multiple entries based on a multimodal interface.

2.4.1 Input Devices

The IW has been used to explore several alternatives to the typical input devices associated with traditional power wheelchairs. As stated in section 2.1.4, voice inputs, eye movement, head movement, among other inputs may be added to IWs. The input devices could be included, since a computer that enables the interface with any type of sensors [16] was incorporated.

Figure 8: Input devices implemented in IntellWheels (adapted from [17]).

A variety of inputs were implemented in the IntellWheels wheelchair in order to give options to the patients enabling them to choose the most adequate and comfortable control mode. The available inputs devices in the IntellWheels project [17] at this point can be observed in Figure 8 and are listed below:

- **USB Joystick** whose implementation was proposed in order to enable the use of shared control technologies, through a basic and known way of driving the wheelchair. Another advantage is that joysticks have several buttons that can be configured to assist in navigation. This input device enables any typical wheelchair user to drive in a straightforward manner the IW prototype.
- **Keyboard** which allows basic control of the wheelchair using some keys in the keyboard in a very standard manner.
- **Head Movements** is an alternative way for driving the wheelchair aimed at users with limited arm mobility. This device is based on an adapted Wii Remote device [17], implemented on a cap. The device captures the relative movement in three axes of Cartesian coordinates through the use of accelerometers.
- **Detection of facial expressions** is used to generate high-level commands for the IW without requiring the use of the hands. These can overcome the difficulty in patients who do not have the ability to make use of the hands, in order to control the wheelchair. The facial expressions were captured by a digital camera and interpreted by an application running on a laptop in the IW. The software included algorithms for digital image processing to detect features, such as colour segmentation and edge detection, followed by the application of a neural network that uses these features to detect the facial expressions. This module allowed a comfortable IW control using facial expressions [157]. However, it was only robust under very stable light conditions. The recognition serves both to address basic commands such as: moving forward, left and stop but also high-level commands: “go to the bathroom” or “go to the room”.
- **Microphone** where the voice can be used to command the IW using a commercial continuous speech recognition software in which a virtual joystick sends commands to the IW control. Before using the voice command, it is necessary to train the software to recognize a set of specific words. The system uses a standard microphone in order to capture the sound and analyses it using the speech recognition module.

After the initial tests with a first, simple prototype, a new prototype was developed with a much more flexible and modular architecture. This second prototype is composed of a commercial wheelchair augmented with the IntellWheels platform (composed by a set of sensors, actuators and a PC) as illustrated in Figure 9.

Figure 9: Prototypes of IntellWheels' Project (adapted from [6]).

This new prototype consists of a Vassillis Electronic Evolution model motorized chair. The wheelchair has an original drive to the electronic system which is fully independent of the type of chair. Thus, the IW platform may be adapted to any type of chair in a very simple way [6].

2.4.2 Sensorial System

One of the concerns of the IntellWheels research team is not to induce major design changes in the wheelchair. The visual impact caused by supports, cameras, sensors, computers, wires, rays and infrared scanners eventually creates psychological barriers to the use of IW. The result is a restriction on the number and use of certain types of sensors due to its characteristics concerning the size and appearance.

Ten sonar sensors have been introduced in a very discrete manner, giving the IW the ability to avoid obstacles, follow walls and perceive unevenness in the ground [17]. Also two encoders were assembled on the wheels providing the tools to measure distance, speed and position and thus use odometry in order to track the wheelchair position in the environment. Two webcams were also included: one directed to the front of the wheelchair, capable of reading ground marks and refine the odometry and the other camera directed to the patient head to detect facial expressions. Other explanations of software design and hardware devices can be found at [17] [156].

2.4.3 Simulator

A 2D simulator was developed which allows the test of control algorithms and to simulate the physical behaviour of the intelligent wheelchair [142] [158]. This simulator was originally based on the *Cyber-Mouse* [159] simulation system. This simulation system is able to represent a virtual area of a building, identical to a hospital or other type of space, with several areas that represent bedrooms, kitchen, bathroom, hall, garden, among others, populated with obstacles (Figure 10). The simulator can simulate all the sensors and actuators of the IW and can manage the movement of several IW within that virtual environment.

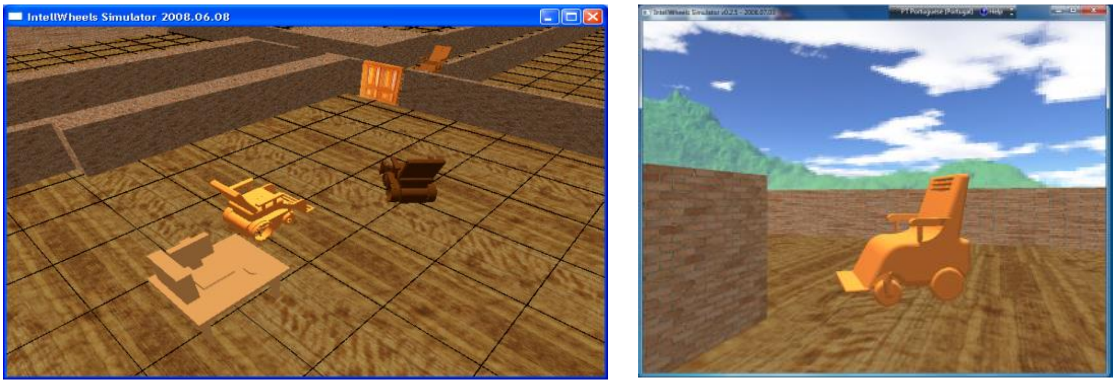


Figure 10: 3D IntellWheels' Simulator (adapted from [160]).

This type of platform has two main objectives: one is the creation of a virtual test based control and interaction of wheelchairs and the other is to test the same interaction between real and virtual chairs. This system allows testing a single wheelchair or multiple wheelchairs in the context of a very complex system, without constrains of the number of real prototypes available.

One of the main innovations of the simulation system is that it allows for mixed reality experiments in which real wheelchairs may interact with virtual wheelchair in a mixed reality environment. Figure 11 shows a conceptual map of the mixed reality information exchange.

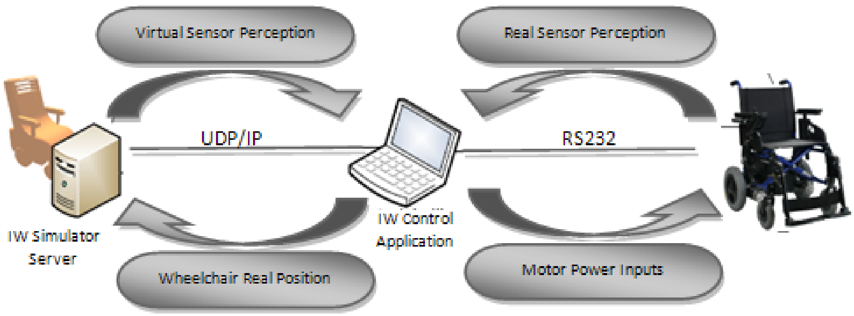


Figure 11: Information exchange in the Mixed Reality (adapted from [160]).

In [158] and [160] more detailed explanation of the simulator and the experimental results of the simulation tests can be found which confirms the importance of the simulator and its contribution for the IW development.

2.4.4 Wheelchair Control Methods

The wheelchair may be controlled using three distinct methods: manual, shared and automatic. In manual control, all navigation is performed by the user without any intervention from the wheelchair. In shared control, the navigation process is divided between patient and machine. In this case, it is the machine which takes control when the navigation of the patient endangers its own safety, in situations such as potential collisions with objects [161]. The computer momentarily takes control and acts on the wheelchair, taking into account the information from sensors and commands from the user. The latter mode of control is the automatic, which enables the computer to take full control over the navigation of the wheelchair and execute task such as navigating from a point to other without any user intervention.

2.4.5 Localization, Vision and Navigation

To help solve the problems related to the Localization, Vision and Navigation specific modules are being developed in IntellWheels project. Therefore an odometry module was developed that based on the information concerning wheels rotation calculates the wheelchair coordinates in the Cartesian space. In the case of real odometry, speed information and position need to be calculated from information provided by the encoders. In the case of virtual odometry, this module is responsible for exchanging data with the simulator and to send it to the control module.

At this stage the vision module processed the images provided by a webcam pointing directly at the front of the wheelchair for navigation purposes. It was very simple and it was used to recognize and follow lines drawn on the floor.

The navigation system is responsible for driving the wheelchair between different locations in the environment. The navigation system in IntellWheels is designed based on a multi-level control architecture [17]. This architecture requires the interconnection of several modules so that it can be controlled. The user control module is the place in which the user defines the type and parameters that the controller will use for automatic mode. After choosing one of seven types of actions (following the line, point, the angle, following the left wall, the right wall, wait, stop) several parameters and configuration fields become available to the user. There is also the possibility of creating a plan of action. In that case the user is asked to select a sequential list of actions to be performed. Once the objective of the current action is completed, this action is deleted and the next action is performed [158]. More details can be found at [142] and [158].

2.4.6 Flexible Interface

The IntellWheels project also aims at developing a flexible framework which may be easily integrated in a commercial wheelchair providing the intelligent capabilities. The new hardware should be blend with the commercial wheelchair with minor adjustments. Another innovation is related with the IW command methodology that is based on a flexible multimodal interface [6]. The wheelchair is commanded using high level language commands like simple expressions "go to bedroom", "follow wall", "wander". However it is important to refer that the input sequences may be used to make any type of combination resulting in different orders. An example of an input sequence could be "blinking the eye" and then say "go" or even give a sequence of inputs from different input devices [6].

The proposed system architecture involves three components: multimodal interface, control interface and input modules. Figure 12 displays the conjunction of these three mechanisms.

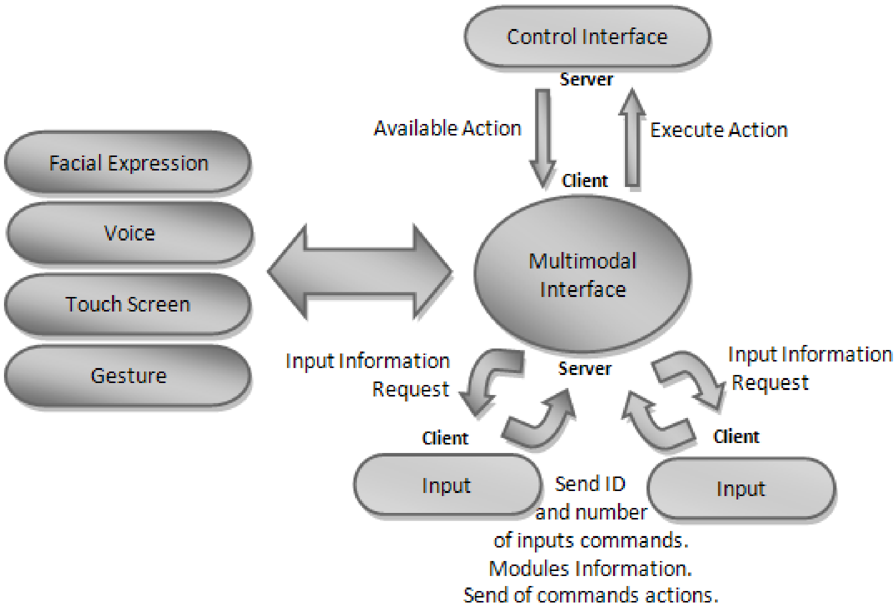


Figure 12: Multimodal Interface architecture (adapted from [6]).

The control interface acts as a communications server to the multimodal interface, in the same manner as the multimodal interface acts as a communications server to the input modules [6]. When the multimodal interface connects to the control interface, the latter sends the information about the available actions. For the input modules, as soon as one of them connects to the multimodal interface, firstly it sends its ID and number of module commands. Secondly, upon the receiving of a request from the interface, the input module sends the description of all the commands.

To control the wheelchair the user must interact with the wheelchair interface by constructing input sequences. Independently from the command being digital or analog the associated event has two identifiers: the module ID and the command number. The search of the input sequence has three available options: if the input sequence occurrence is unique then the composed sequence can be immediately analysed; if there are more occurrences of the same sequence fragment these must be further processed and finally if the occurrence does not exist in the list like choice error the process is automatically stopped. If the search indicates that the occurrence is not unique the algorithm waits for a given predefined time for more input events [6].

Figure 13 presents the IntellWheels Multimodal Interface (IMI) design and all the available components.

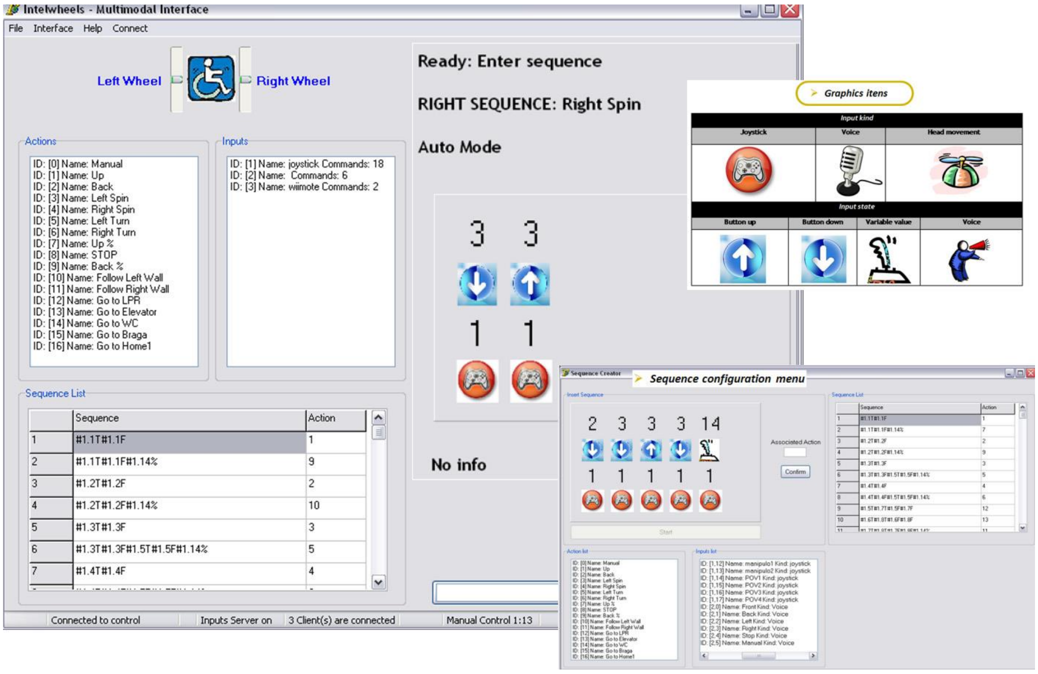


Figure 13: IntellWheels' multimodal interface design (adapted from [6]).

As it may be analysed in Figure 13, the information displayed at the multimodal interface contains several items such as: a list of available actions; a summary of the connected inputs; input devices and control connections status; input sequence graphical information; sequence's list and analysis result; wheels speed information and menus for programming the interface options and adding more sequences.

2.5 Conclusions

The main focus of this chapter was on the state of the art on Intelligent Wheelchairs and simulators as important instruments for testing and training. The chapter also contains a description of adaptive interfaces, the inputs devices that can be applied in the intelligent wheelchairs and how a multimodal interface, following several principle designs, can be used. Finally, a general description of the IntellWheels project is presented including a brief description of the main details that were implemented in the project initial phase.

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.

IntellWheels project is aiming at developing a new concept of Intelligent Wheelchair. The prototype is controlled using high-level commands, triggered using combinations of distinct inputs in the context of a multimodal interface. However, in order to fully control the wheelchair, the user must have a Wheelchair interface adapted to his characteristics. And for that, the system (wheelchair and/or user) must be able understand what are exactly the user characteristics in what concerns interacting with the wheelchair.

The next chapter will focus on the state-of-the-art concerning knowledge discovery algorithms and techniques that may be used in the context of this project, mainly to respond to the objectives of creation of an adapted command language and a suitable interface to the wheelchair's user. The applications of knowledge discovery methodologies are finally presented focusing on applications on the health's area.

Chapter 3

3. Knowledge Discovery

Knowledge discovery and data mining are areas of growing interest in the context of academic research, science, society and in business intelligence. There is an enormous amount of available data which, if correctly analysed, can give a lot more information than the one that is easy accessible directly from it. Nevertheless, it is necessary to follow some steps for extracting the information with more accuracy, namely: problem modelling, data selection, task pre-processing, transformation, task definition, algorithms' modelling and application in data mining, evaluation, interpretation and decision. There are several proposals to standardize the process for extracting knowledge from data. The classical approach of Knowledge Discovery in Databases (KDD) was proposed by Fayyad et al. [162] in 1996. The effort to present an approach in this field was also made by the industry. It was necessary to obtain a methodology that could be applicable to industrials procedures. Examples of these methodologies are SEMMA (Sample, Explore, Modify, Model and Access) and CRISP-DM (Cross-Industry Standard Process for Data Mining).

This chapter presents the classical approach of Knowledge Discovery in Datasets and the SEMMA and CRISP-DM standards. Next a more detailed description about the general phases and applications is presented.

3.1 Standards to Extract Knowledge from Data

3.1.1 KDD - Knowledge Discovery in Databases

The process of extracting knowledge from databases has several phases as proposed by Fayyad. Figure 14, shows an overview of the steps that compose the extraction of knowledge [162].

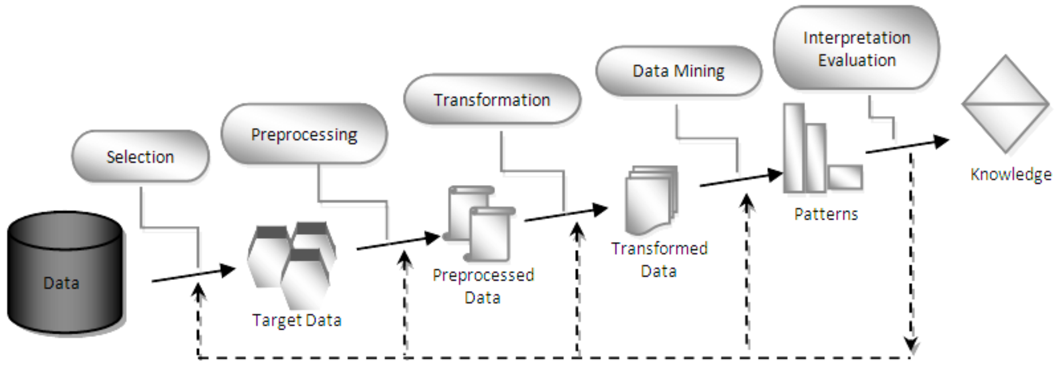


Figure 14: Process of KDD (adapted from [162]).

The selection phase has the objective of acquiring the most appropriated subset of data. Then the pre-processing phase consists in cleaning the data and dealing with missing values. The transformation stage is important for standardize data. The next step is data mining which involves the search of relationships and global patterns that exist in large databases. These relationships represent valuable knowledge. Interpretation and evaluation phase is important to evaluate the induced model and the results and finally, the decision by the extracted knowledge [162].

3.1.2 SEMMA – Sample, Explore, Modify, Model and Access

The SEMMA standard was proposed by SAS Institute together with the software Enterprise Miner [163]. It is advocated to be a logical organisation of the functional tool set of SAS Enterprise Miner for carrying out the core tasks of data mining. The process is composed of five phases: Sample, Explore, Modify, Model and Access. Figure 15 presents the phases in a schematically way.

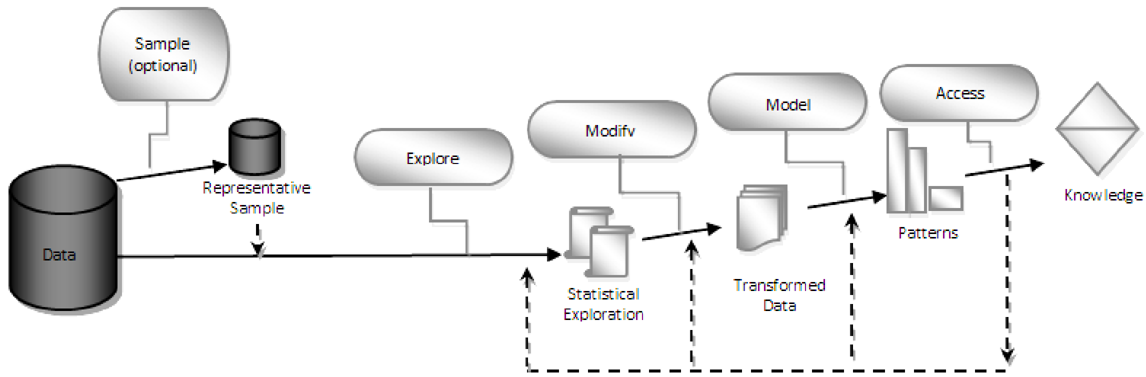


Figure 15: Process of SEMMA.

The first stage *Sample* consists in obtaining a representative sample of the data that has significant information, however small in order to be quickly manipulated. This first phase is optional, nevertheless mining a representative sample instead of the whole volume reduces the processing time required to get information. Moreover, if general patterns appear in the data as a whole, these will be traceable in a representative sample [164]. After that follows the *exploration* of the data. In this stage (*Explore*) an investigation about trends and anomalies is performed with the objective of obtaining information about the data. The third phase is the *modification* of data. The data is modified for creating, selecting and transforming the variables for the study. The *Model* stage consists in creating the process where the rules and patterns translate the desired outcome. Finally, the *Access* consists in evaluating the usefulness and reliability of the findings from the DM process and estimating how well it performs. It is possible, by evaluating the results in each phase of the SEMMA process, to have new questions and proceed back to the exploration phase for additional refinement of the data.

This scheme has obviously similarities with KDD. It is possible to find studies that were conducted in order to compare both standards [165] [166] and some conclusions were achieved. The Sample phase can be identified with Selection. However that, it is clearly stated in SEMMA, that the Sample is an optional stage. Explore can be recognized as Preprocessing, Modify can be identified with Transformation; Model can be identified with Data Mining and Assess can be identified with Interpretation/Evaluation. The comparative study also involved a well-known standard the CRISP-DM that it is explained in the next subsection.

3.1.3 CRISP-DM - Cross-Industry Standard Process for Data Mining

Cross-Industry Standard Process for Data Mining (CRISP-DM) [167] is another standard process to clarify and help with the extraction of information. This was created with the goal of developing a standard process model to service the data mining community and it was proposed by a joint project between the European Union and a group of four companies: Daimler-Benz (now DaimlerChrysler [168]), Integral Solutions Ltd. (ISL) now part of IBM-SPSS [169], NCR [170] and OHRA [171]. Figure 16 shows the phases of the CRISP-DM standard.

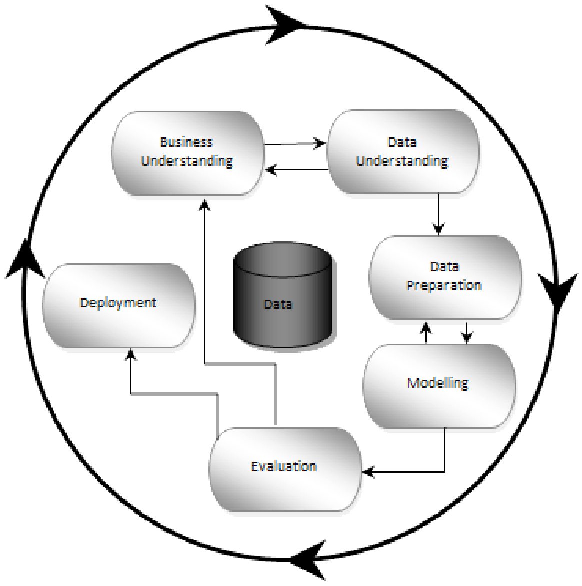


Figure 16: Process of CRISP-DM (adapted from [171]).

The method organizes the process in six phases: Business understanding; Data understanding; Data preparation; Modelling; Evaluation and Deployment.

Clearly an initial stage focusing in the objectives of the project and making the definition of the data mining problem with a subsequent plan to solve is a major step and a novelty relative to the two previous standards. Very important elements, such as, the business's objectives, requirements, constraints and resources available for the project, in order to establish the data mining goals are detailed in this first stage. The next steps are similar to the KDD and SEMMA steps and finally the Deployment is related with the actual application of the models. Based on the requirements, this phase can pass through a simple report or implementing a repeatable data mining process [171].

3.2 Techniques to Extract Knowledge from Data

The next section presents the phases in a more detailed manner and with some examples of techniques that are used to elaborate this kind of analysis. The classical KDD approach serves as starting point for the phase's descriptions.

3.2.1 Types of Data and Data Selection

The available data may differ in a number of ways. The attributes used to describe data objects can be qualitative or quantitative and data sets may contain objects with explicit relations. In fact, the type of data is one major condition to determine which tool and techniques can be used to analyse the data.

A data set can often be viewed as a collection of data objects and each object is defined by several attributes that capture the characteristics of the object. Characteristics may vary, so four types of attributes can be defined: nominal, ordinal, interval and ratio. The first two are referred to as qualitative or categorical attributes and the last two are referred to as quantitative or numeric attributes. An autonomous way of distinguishing between attributes is the number of values they can take. If an attribute has a finite or a countable infinite set of values it is classified as discrete while if attribute values are real numbers then it is classified as continuous.

There are several questions related to data such as outliers, missing values or even superfluous variables that need cleaning and transformation tasks.

3.2.2 Pre-processing

The input data can be stored in many different formats and could be on a repository or distributed across multiple locations [172] [173]. The objective of pre-processing is to transform the raw input data into an appropriate format for posterior analysis. Nowadays, there are several strategies and techniques to make the data more suitable for data mining with respect to time, cost and quality. The rest of the section presents a brief description of these techniques; a more detailed description is available at [172].

- Aggregation – the objective is to obtain smaller data sets that can reduce the required memory and processing time. It is possible to condensate information by aggregating several entries in a more general one, as when, instead of working with all days in a year, data is organized by months;
- Sampling – if a representative sample of data is chosen it is possible to obtain good results and use more computationally intensive algorithms using only that sample, hence avoiding time consuming processing with all the data;
- Dimensionality reduction – data sets can have a large number of features, however it may be important to reduce it since there are obvious advantages to interpret a model that uses fewer features, since it is much easier to visualize [174] and understand the data, for example. In fact, there are reduction techniques, such as Principal Component Analysis, to create new attributes that are a combination of the old attributes [175]. Another way to reduce the dimensionality is eliminating irrelevant and redundant features. This can be done by using three standard approaches to feature selection: embedded (which occurs as a part of the data mining algorithm); filter (the features are selected before the data mining algorithm is running) or wrapper (these methods use the target data mining algorithm as a black box to find the best subset of attributes).
- Feature creation – to capture more effectively the information on a data set it is possible to create a new set from the original attributes. The number of attributes on the new set should be smaller allowing to benefits from dimension reduction.

- Discretization and binarization – since some data mining algorithms require that the data must be categorical it may be desirable to change a continuous attribute into a categorical one (discretization) and both continuous and discrete into one or more binary attributes (binarization).

3.2.3 Transformation

A variable transformation refers to a transformation that is applied to all the values of the variable, for example simple functional transformations and normalizations. The first type of variable transformation is application of a mathematical function to each value of the variable. For example in Statistics it is usual to use logarithmic, square root or inverse proportion to transform a variable which does not have a normal distribution. The second type of transformation is the normalization or standardization. It is common to use this kind of transformation to avoid having a variable with large values dominating the results of the calculation [172].

These introductory phases are important for understanding the data to be analysed and to allow the best choices for the subsequent data mining task.

3.2.4 Data Mining, Statistics, Artificial Intelligence and Machine Learning

The concept of Data Mining appeared in the eighties but it is claimed by Lovin [176] that the first work on data mining was presented in 1662 by John Graunt with an attempted model to predict the next bubonic plague in London by making a statistical analysis of the mortality in those years. Today, data mining involves areas that are powerful tools on data analysis and a definition could be “the exploration and analysis by automatic or semi-automatic means of large quantities of data in order to discover meaningful patterns or rules” [177]. Some of the areas are Statistics; Artificial Intelligence (AI) and Machine Learning (ML).

Tools and techniques of classical statistical analysis play a significant role in data mining. Without most of the concepts derived from statistics there would be no data mining algorithms. In fact, these areas are the foundation of most technologies on which data mining is built. Regression analysis, standard distribution, standard deviation, standard variance, discriminant analysis, cluster analysis and confidence intervals are used to study data and data relationships. Artificial Intelligence (AI) is another area in which data mining concepts are based. AI is built upon heuristics as opposed to statistics and attempts to apply human-like reasoning processing to statistical problems. This approach requires large computer processing and it was not practical until the early eighties [178]. AI found a few applications at the scientific/government markets, but the required supercomputers of that period of time make most of the AI applications out of reach of the common citizen [178].

Machine Learning is described as the blending of statistics and AI. While AI was not a commercial success, its techniques were adopted by Machine Learning. Machine Learning is considered an evolution of most AI algorithms, since associate AI heuristics with advanced statistical analysis [178]. Machine learning attempts to let computer programs learn about the data they study, resulting in programs that make different decisions based on the qualities of the studied data, using statistics for primary concepts, and adding more advanced AI heuristics and algorithms to achieve its objectives [178].

The problems that are proposed to be solved can be of classification or regression. The difference between them is concerned with the class categories. For the first one it is designated nominal variable, but for regression problems the classes are numeric.

3.2.4.1 Data Mining Tasks

Data Mining tasks can be divided in two large categories: Predictive and Descriptive [172]. The objective of predictive tasks is to predict the value of a particular attribute (dependent variable) based on the values of others attributes (independent variables). The purpose of descriptive tasks is to derive patterns that summarize the underlying relationships in data. An exploratory analysis is carried on and frequently requires post-processing techniques to validate and explain the results.

An alternative categorization for data mining tasks is presented at [179] in which Data Mining tasks are divided in five groups:

- Predictive Modelling - where the goal is to predict a specific attribute based on the other attributes in the data;
- Clustering - targets grouping the data records into subsets where items in each subset are more similar to each other than to the items in other subsets;
- Dependency Modelling - targets modelling the generating joint probability density function of the processes that could have generated the data;
- Data Summarization - find out summaries of part of the data, like similarity between a few attributes in a subset of data;
- Change and Deviation Detection - these methods account for sequence information, such time-series or some other ordering. In this case it is possible to considerer the order in which the observations are presented in the data.

3.2.4.2 Classification Techniques

The tasks of classification involve the assignment of objects to one of several predefined categories. The classifications techniques and the methods for evaluating and comparing the performance of classification techniques are presented below.

Definitions and Formalizations

A classifier is a function (Equation 1) that, for a new example (or object), returns a correspondent class. In a mathematical point a view a classifier is a function:

$$f : X \to C \qquad \textbf{(Eq 1)}$$

where $\mathbf{x_i} \in X$ is an object and C is the set composed by the classes.

Supervised learning is the task to induce a classifier that can predict with high performance the classes of new examples from the training set with previous classified examples. So the ultimate objective is to find the correct function that is hidden on the data [179]. The target function is also known as the classifier model [172].

The formalization of dataset is essential to understand the construction of the classifier. Considering N training examples which could be denoted by a tuple ($\mathbf{x_i}$, y_i) with i = 1, 2, …,N, where $\mathbf{x_i} = (x_{i1}, x_{i2}, \ldots, x_{id})^T$ corresponds to the attribute set for the i^{th} example and y_i denote its class label. If the classification is binary the class label could be for instance yes/no; 0/1; -1/1 or examples with the option to be positive or negative.

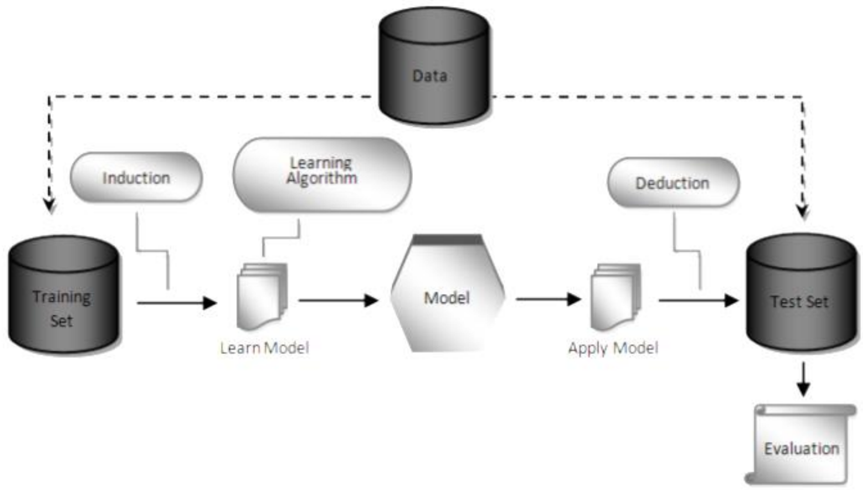


Figure 17: General approach for building a classification model (adapted from [180]).

A classifier is a systematic approach for building classification models from input data. There are different techniques and each technique employs a learning algorithm to identify the model that best fits the relation between the attribute set and the class label of the input data. One of the principal objectives of the learning algorithm is to construct a model with good generalization capability to predict the class labels of previously unknown records. Samples in the past are analysed and generalized for future cases [180]. Figure 17 represents the general approach for building a classification model.

The data can be separated into training data which by induction and applying a learning algorithm it is possible to construct a model. The other part of data, called test data, is used to evaluate the constructed model. Next, it is described the state of art of learning algorithms for creating classification models.

Decision Tree

A Decision Tree is an approach for constructing classification models which does not require any assumptions regarding the type of probability distributions satisfied by the attributes and the class. Nevertheless, there are huge efforts in this research field to find new approaches for have quicker results such as heuristics solutions [172]. Decision trees have a high degree of interpretation. A complex decision is divided in a sequence of elementary decisions. The construction of decision trees is based on several steps. The inputs to this algorithm consist of the training instances E and the attribute set F. The algorithm proceeds recursively selecting the best attribute to split the data and expanding the leaf nodes of the tree until a stopping criterion is achieved. Decision trees can be over-elaborated and over fitting which are problems susceptive to occur. Therefore after building the decision tree a tree-pruning step can be performed to reduce the size of the decision tree and improve its generalization capability.

Rule-Based Classifier

A rule-based classifier is a method for classifying records using a collection of “if - then” rules. To build a rule-based classifier it is important to extract a set of rules that identifies key relations between the data attributes and the class label. There are direct and indirect methods for extracting classification rules. The direct methods extract the classification rules directly from data while the indirect ones extract such rules from other classification models, like decision trees. There are several algorithms for finding the best classification rules, as for example OneR [181] or Ripper [182].

Nearest-Neighbour Classifier

A Nearest Neighbour classifier represents each example as a point in a d-dimensional space, where d is the number of attributes. Given a test example the proximity to the other data points in the training set is computed, using a measure of similarity or dissimilarity, such as the Euclidian distance or its generalization, the Minkowski distance metric, the Jaccard Coefficient or Cosine Similarity [172]. The k- nearest neighbour (k-NN) of a given example refers to the k points that are closest to the example. Figure 18 display representations for k = 1 and 3.

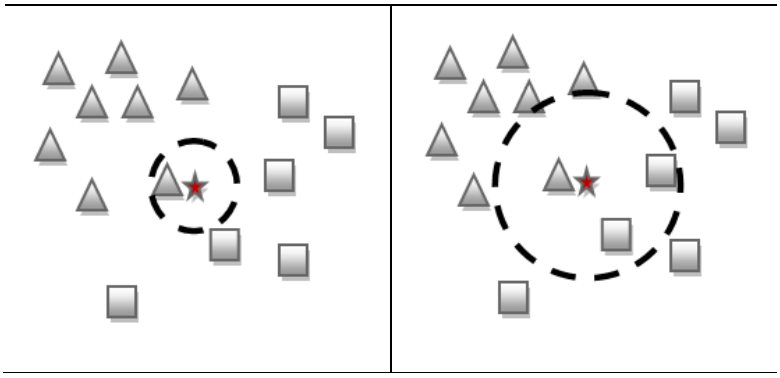


Figure 18: Representations of 1 and 3 NN.

One of the main points that characterize k-NN is its insertion in the category of lazy learners, since they do not require building a model and only make their predictions on local information. However, classifying a test example is an expensive task because it is necessary to compute the proximity values between the test and all the training examples. An important decision is the choice of the proximity measure since a wrong choice can produce wrong predictions.

Bayesian Classifiers

Bayesian Classifiers are based on models of the probabilistic relationships between the attributes and the class.

Naïve Bayes is a Bayesian classifier which presents the probability of an object and which applies the Bayes Theorem to produce the classification. The Naïve Bayes classifier assumes that the presence of a particular feature of a class is unrelated to the presence of any other feature. An advantage is that it requires a small amount of training data to estimate the parameters necessary for classification. Because independent variables are assumed, only the variances of the variables for each class need to be determined and not the entire covariance matrix [183]. The algorithm and applications can be found at [183].

Artificial Neural Network

An Artificial Neural Network (ANN) is a mathematical/computational model that attempts to simulate the structure of biological neural systems. The ANN consists of an interconnected group of artificial neurons and processes information using a connectionist approach. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. Figure 19 presents an example of a simple ANN.

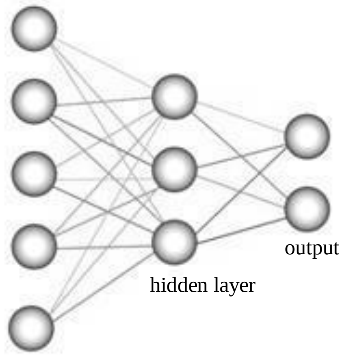


Figure 19: Simplified view of an artificial neural network (adapted from [184]).

The neurons are identical units that are connected by links. The interconnections are used to send signals from one neuron to the other [185]. The concept of weights between nodes is also present since it is used to establish the importance from one connection to the other. The network may contain several intermediary layers between its input and outputs layers. The intermediary layers are called hidden layers and the nodes embedded in these layers are called hidden nodes. In a feed-forward neural network the nodes in one layer are connected only to the nodes in the next layer. The Perceptron is the simplest model since it does not use any hidden layers.

The ANN can handle redundant features since the weights are automatically learned during the learning phase. Hence, the weights for redundant features tend to be very small. A gradient descent method is used for learning the weights which often converges to some local minimum; however one way to minimize local minimum effects is to add a momentum term [172] to the weight update formula. Another known characteristic concerns high training time for the ANN, especially when the number of hidden nodes is large.

In [186] the data mining based on fuzzy neural network is researched in detail and also the key technologies and ways to achieve the data mining based on neural networks.

Support Vector Machines

A Support Vector Machine (SVM) is a technique based on statistical learning theory which works very well with high-dimensional data and avoids the curse of dimensionality problem [172]. The objective is to find the optimal separating hyperplane between two classes by maximizing the margin between the classes' closest points.

There are several cases which should be studied. Figure 20 presents the simplest one, since it is the case of linearly separable classes with class +1 and class -1.

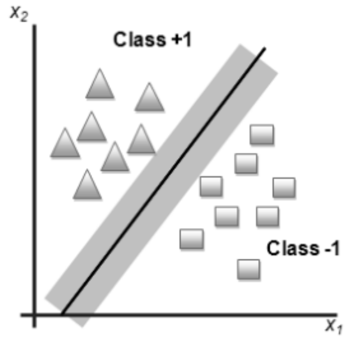


Figure 20: Linear decision boundary – separable case.

This can be interpreted to an optimization problem with

$$\min_{\mathbf{w}} \frac{\|\mathbf{w}\|^2}{2} \quad \textbf{(Eq 2)}$$

subject to the following condition:

$$y_i(\mathbf{w}\cdot\mathbf{x_i}+b)\geq 1 \text{ where } i=1,2,...,N \quad \textbf{(Eq 3)}$$

where $\mathbf{w}\cdot\mathbf{x_i}+b=0$ is the hyperplane of a linear classifier which maximizes the margins and y_i represents the class. The points on the boundaries are called support vectors.

There are solutions for multiclass problems and for the cases that are not linearly separable. These explanations can be found at [172] [187] [188].

Classifier Combination Methods

The classifier combination or ensemble methods construct a set of base classifiers from training data and perform the classification by taking a vote on the predictions made by each base classifier. Figure 21 shows a scheme that resumes the process of ensemble methods. The first step represents the creation of multiple data sets; the next steps are building multiple classifiers and finally combining the results of the classifiers.

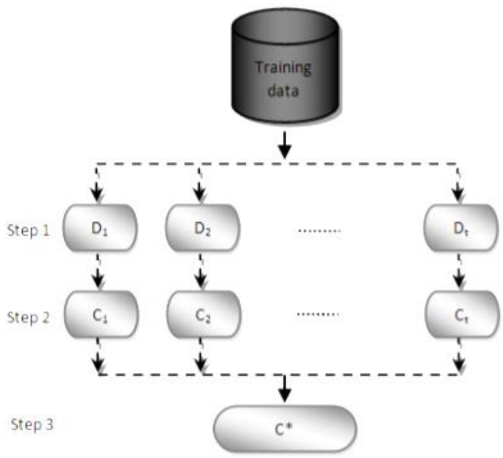


Figure 21: Scheme of the process of ensemble methods (adapted from [172]).

The combination of classifiers can be performed using different approaches: by manipulating the training set, the input features, the class labels or even manipulating the learning algorithm [189]. The first three approaches can be applicable to any classifier and the fourth approach depends on the type of classifier used.

3.2.4.3 Association Techniques

Association analysis is an approach for discovering relationships hidden in large data sets. The uncovered relations can be represented in the form of sets of frequent items or association rules. An association rule is an implication expression of the form $X \rightarrow Y$ where X and Y are disjoint itemsets (set with one or more categorical values). To measure the strength of an association the support and the confidence are used. The support calculates how often a rule is applicable to a given data set and the confidence determines how frequently items in Y appear in transactions that contains X.

Given a transaction set T, the objective is to find all the rules for which support and confidence are bigger than a certain threshold. The approach can be executed in two steps. The first step is to generate all the frequent itemsets, the objective is to find all the itemsets that satisfy the support and confidence thresholds, the second task is the rule generation whose objective is to extract all the high-confidence rules from the itemsets found in the previous step.

Association analysis has several applications and has been applied in different areas such document analysis [190], web mining [191] or even bioinformatics [192]. Moreover, other learning problems have been studied using association analysis like classification, regression and clustering [193] [194].

3.2.4.4 Cluster Analysis

Cluster analysis is typically considered an unsupervised classification. In fact, supervised classification is different because new unlabelled objects are assigned a class label using a model developed from objects with known class labels.

Given N samples characterized by their attributes, the objective of clustering is to obtain groups (clusters) of samples with high variance among the groups and high similarity between samples in the same group.

The types of clustering can be divided in two major ways: hierarchical and partitional. Figure 22 shows hierarchical and partitional examples.

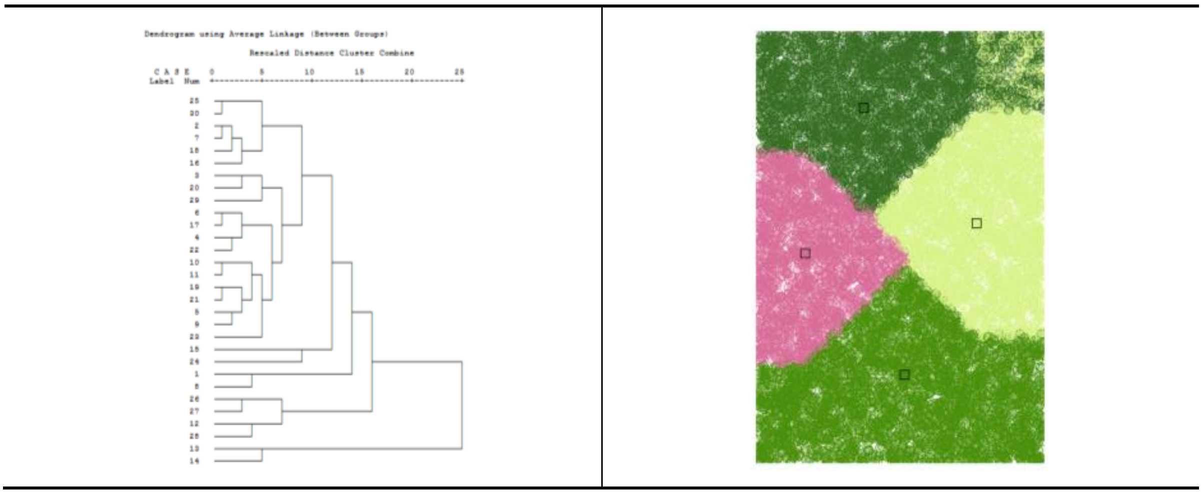


Figure 22: Hierarchical and partitional examples of clustering types.

The first type is a set of nested clusters that are organized as a hierarchical tree, the second is a simple division of the set of data objects into non-overlapping clusters such that each object is in exactly one subset.

A well-known technique for cluster analysis is the K-means [195] which is a partitional technique that attempts to find a number of clusters (K) which are represented by their centroids and are first defined by the user. An approach of hierarchical technique is Agglomerative Hierarchical Clustering which starts with each point as a singleton cluster and then repeatedly merges the two closest clusters until a single cluster is formed. There are also other clustering algorithms also based in partitional clustering but influenced by the density of the objects [196] [172]. Besides the usual clustering it is also present in literature other methods, such as, semi-supervised clustering. Instead of finding groups as in usual unsupervised clustering algorithms, semi-supervised try to improve clustering results by employing external knowledge in the clustering process [197].

Cluster evaluation and validation should be important tasks in cluster analysis, since every clustering algorithm will find clusters in data even if there is not a natural cluster structure or if the number of clusters is not the most correct. Compare sets of clusters and determine which is better or even comparing the results of a cluster analysis to known results provided for example by class labels are strategies for cluster evaluation and validation.

In fact, evaluation is an important phase not only for clustering but also for supervised classification in which the evaluation of the resulting classification model is an integral part of the process of constructing a classification model. The next chapter describes several measures and procedures in order to find the best interpretation and evaluation of this kind of classification models.

3.2.5 Interpretation and Evaluation

The final stage of KD is the interpretation and evaluation of the results. After this step, either the process can be finalized and the required knowledge can be obtained, or the developer should go back and repeat previous phases (changing some parameters) in order to improve the final results.

This section presents several methods for evaluating the performance of a classifier and for comparing the performance of two classifiers.

Performance evaluation of a classification model is based on the counts of test records correctly and incorrectly predicted by the model. These counts are written in the confusion matrix [134].

Definition 4: The confusion matrix can be designated as in Equation 4:

$$CM = (n_{ij})_{\substack{i=1,\ldots,N \\ j=1,\ldots,N}} \quad \textbf{(Eq 4)}$$

where n is the number of cases, i designate the lines and j the columns of the matrix.

Example 4: Table 5 shows an example of a confusion matrix with five classes, the columns represent the correct class and the lines represent the predicted classes.

		True				
		I_1	I_2	I_3	I_4	I_5
Predicted	I_1	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}
	I_2	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}
	I_3	n_{31}	n_{32}	n_{33}	n_{34}	n_{35}
	I_4	n_{41}	n_{42}	n_{43}	n_{44}	n_{45}
	I_5	n_{51}	n_{52}	n_{53}	n_{54}	n_{55}

Table 5: Example of a confusion matrix with five classes.

Although this matrix provides the necessary information to determine how well a classification model performs, it is important to compare the performance of different models with just one single measurement. This can be done using accuracy or error rate. Accuracy is the ratio between the number of correct predictions over the total number of predictions while the error rate is the ratio between the number of wrong predictions over the total number of predictions.

There are in literature several measures that can derive from the confusion matrix [198] [199]. Liu et al. [200] presented a list of these measures to compare the performance of different classifiers. They presented a comparison of the measures and of the correlation between them. The overall accuracy, the average accuracy of recall and precision, the classification success index, the average of Hellden's [199] mean accuracy index, the Kappa measure [198] are examples of some of the studied measures. They concluded that the primary measures are the recall, precision and overall accuracy.

Recall and Precision are two more metrics employed for studying more precisely the distribution and prediction of classes and this method is especially useful when the successful detection of one of the classes is considered more significant than detection of the others classes [172]. Precision can be seen as a measure of exactness and Recall as a measure of comprehensiveness. To formalize these concepts the precision is the ratio between the true positive over the total number of true and false positive, while the recall is the ratio between the true positive over the total number of true positive and false negative.

Moreover, there are several methods for estimating the generalized error of a model during training, in order to find a model with a manageable complexity and not susceptible to overfitting. The recommended methods for evaluating the performance of a classifier are: Holdout method; random subsampling, cross-validation and bootstrap [172].

The Holdout method is appropriate for a large set of data and the process is to divide the original data with labeled samples in two parts, called the training and the test sets. Normally the division is done fifty-fifty or two-thirds for training and one-third for testing [172]. A classification model is then induced and evaluated using the testing set. Several limitations may be appointed to this method, as the limitation on the number of training labeled samples; the model may be highly dependent on the composition of the training and test sets; finally the training and test sets are subsets from the original data, so a class can be over represented in one subset and underrepresented in the other [172].

An alternative to overcome these handicaps is the second method, Random Sampling, which repeats the Holdout Method several times to improve the estimation of a classifier's performance. However this method has some problems as it does not use as much data as possible for training and has no control over the number of times each record is used for testing and training. This method is recommended for sets with an intermediate size of about 1000 samples.

Cross-Validation is an alternative to Random Subsampling. Here each record is used the same number of times for training and exactly once for testing. The procedure initially begins with the division of the dataset into k equal-sized partitions. Then a classifier is applied to construct a model using k-1 partitions and test it on the remaining partition. This step is repeated k times, each time using a different partition as the test set. If the number k is equal to the number of samples the method is also called leave-one-out. Finally, in the Bootstrap technique the examples are sampled with replacement, that is, a record already chosen for training is put back into the original set in which it has the same probability of being chosen again. Examples that are not included in the Bootstrap sample became part of the test set [172].

Another line of study is concerned with answering the question of the required dimension of the training set using the different classifiers. The construction of the learning curve is an appropriate method and the procedure firstly divides the dataset into two parts and with an incremental ratio, usually of 5%, iteratively adds this percentage of examples into the training subsets and then calculates the performance values on the fixed test set.

To establish which classifier works better with a specific data set it is common to use the abovementioned measures. However, it is important to know if the performance of the classifiers is statistically significant. In fact, if a classifier presents a higher accuracy but a small data set was used, which is the confidence level of that accuracy. To considerer this latest issue, some statistical tests are presented below that can be performed to compare the results of classifiers and to observe the confidence in some kind of measure.

To obtain the confidence interval it is necessary to characterize the probability distribution function of the accuracy measure. For example the task of predicting the class labels can be modelled by a Binomial Distribution and if the size is big enough can be approximated by a Normal Distribution and the confidence interval for accuracy (*acc*) can be extracted from:

$$P\left(-z_{\frac{\alpha}{2}} \leq \frac{acc-p}{\sqrt{p(1-p)/N}} \leq z_{\frac{\alpha}{2}}\right) = 1-\alpha \qquad \textbf{(Eq 5)}$$

where p is the true accuracy of the model, N the size of samples and $-z_{\frac{\alpha}{2}}$ and $z_{\frac{\alpha}{2}}$ are the lower and upper bounds obtained from the standard normal distribution at confidence level $(1-\alpha)$.

To compare two models that are evaluated on two independent test sets a hypothesis test (independent samples) should be applied and if the objective is to compare two classifiers in the same data set a paired samples test should be applied. This can be extrapolated for more than two models and ANOVA should be applied for independent samples and Repeated Measures for paired samples.

There are others measures for evaluating the performance of the options taken during KD process: time to construct the model (training time); time to use the model (classification/prediction time); Robustness by handling noise and missing values; Scalability because of efficiency in disk-resident databases; Interpretability by understanding and insight provided by the model.

In conclusion the performance of a model depends of the learning algorithm and others constraints such as the distribution of data, the cost associated with misclassification and the size of training set, among others.

3.3 Online and Evolution Learning

The process of Knowledge Discovery is still an emergent area and there is a lot of recent research on online and evolution learning. In fact, there are several algorithms that can be applied to data stored in datasets. However, the acquisition of data can be done online and change with time, making the current models obsolete if the new data changes the patterns. This chapter presents an overview of the online and evolution learning and the new perspectives to deal with data.

3.3.1 Data Stream Mining

Data stream can be defined as a continuous and varying sequence of data that incessantly arrive at a system to store or process [201] [202]. More particularly, data stream mining is the process of acquiring informational structure, such as models and patterns, from continuous data stream [202]. The data mining approach can deal with large datasets, however it cannot address the problem of continuous supply of data [203]. In fact, a model that was created cannot usually be updated when new data arrives and since data streams may produce huge volumes of data most of the times it is impossible to store it [202]. Many issues are imposed to investigation to overcome these kinds of problems. The design of fast mining methods for data streams, the need to detect changes and different data distributions and real-time applications are some of the challenges.

3.3.1.1 Types of Data and Data Sources

The data obtained by data stream can be classified at a high level into two categories, as it is defended in [204] [201]:

- Transactional Data Streams – This type of data streams refers to logs of interaction between entities. Examples of Transactional Data Streams are the logs that result from the interaction of users with a web site.
- Measurement Data Stream – These kinds of data streams are produced as a result of recording the state of entities such as sensors or large-scale communications networks which need continuous monitoring.

A data stream can be obtained on several different fields and normally they are in great quantities, ordered, fast changing and possibly unlimited, as, for example, the raw data from the sensors of a brain computer interface. For these reasons and since typically data mining methods require multiple scans to data, it is very important to modify mining techniques for stream data applications [202].

3.3.1.2 Stationary Data Stream Learning

The principal characteristics of the data stream model involve some constraints, such as the impossibility of storing all data from the data stream; the arrival speed of data stream forces each example to be processed mostly in real time discarding it afterwards and the distribution that generates the items can change overtime making past irrelevant or detrimental. The first constraint limits the memory that the algorithms can use to treat the data streams. The second is concerned with the time that an item can take to be processed. These constraints lead to the development of data stream summarization techniques. The last constraint is ignored in several approaches and these can be classified as Stationary Data Stream methods. Other fields of research consider the third constraint and are classified as Evolving Data Stream Learning.

3.3.1.3 Evolving Data Stream Learning

As explained in the last section the approaches that use the evolution concept consider the data stream distribution can change over time. Because of that, it is important to present the methodologies, algorithms and adaptations made in order to reflect this kind of modifications.

Concept Drift

The *concept drift* has been defined as the change over time and an unexpected behaviour of statistical proprieties of the target variable [205] [206] [207]. It can also refer to other kind of objective besides the target, such as an input.

Moreover, several machine learning algorithms are presented to deal with data streams.

Algorithms for Mining Data Streams

The algorithms presented in literature and related with data streams and concept drift are divided into different objectives and techniques [208]. Clustering, classification, frequency counting, time series are some of the areas where the techniques of mining data streams were applied [208].

Clustering data streams using k-median technique was a subject published by Guha et al. [209]. The objective was to maintain consistently good clustering of the observed sequence, using small amounts of memory and time. A constant-factor approximation algorithm was used for the k-median problem in the data stream model of computation in a single pass. Ordonez [210] has proposed variants of the k-means to cluster binary data streams. The focus was to speed up and simplify the process of having a set of statistics and operations with sparse matrixes. The algorithm Balanced Iterative Reducing and Clustering using Hierarchies (BIRCH) presented by Zhang et al. [211] attempts to find a good clustering with a single scan of the data and improves the cluster quality with a few additional scans.

Hulten et al. presented the Concept-adapting Very Fast Decision Trees (CVFDT) to deal with concept change [212]. This algorithm is an extension of the Very Fast Decision Tree (VFDT) [213] inspired in the Hoeffding Tree Algorithm [213]. They applied this principle to classification and clustering problems [208]. Gaber et al. [214] proposed the Lightweight Clustering (LWC) and the Lightweight Classification (LWClass) algorithms. The approach is to dynamically adapt the data-stream mining process based on the available memory resources. The Ultra-Fast Forest of Trees (UFFT) was presented by Gama et al. The UFFT is a supervised learning algorithm that generates a forest of binary trees. This algorithm works online, uses the Hoeffding bound to decide when to install a splitting test in a leaf leading to a decision node. The algorithm builds a binary tree for each possible pair of classes, leading to a forest of trees to deal with multiclass problems [215]. The On Line Information (OLIN) algorithm was presented by Last [216]. The OLIN is an online classification system, which dynamically regulates the size of the training window and the number of new examples, between model re-constructions to the current rate of concept drift [216].

Methodology for Adaptive Stream Mining

Bifet et al. [203] defended that it is advised to use a well-designed scheme for dealing with the major steps of study in the data stream mining: remember recent examples; detect distribution changes and how to model upgrade.

The proposed methodology [203] presents three modules: Memory; Estimator and Change Detector as can be observed in Figure 23.

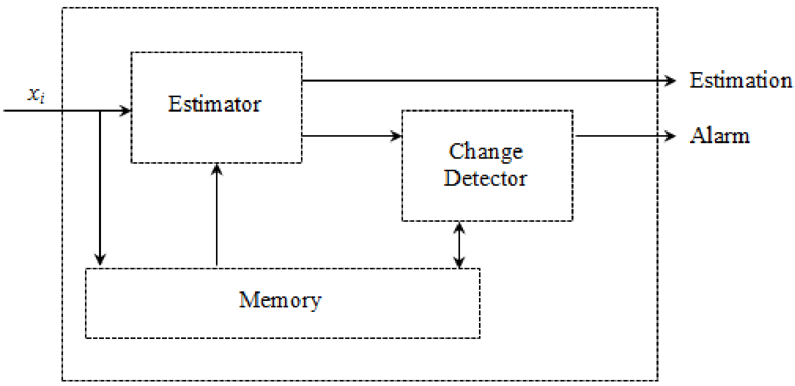


Figure 23: Approach for adaptive stream mining (adapted from [203]).

The input of this algorithm is a sequence of data $\boldsymbol{x_i}$ whose distribution is unknown. The outputs are at each time step an estimation of important parameters of the input distribution and a signal alarm indicating that the distribution changed recently [203].

The Memory Module stores all the sample data and summary that it is relevant at current time and shows the current data distribution. The Estimator Module is an algorithm that estimates the statistics on the input data which may change over time. This algorithm may use the information in the memory module. The Change Detector Module outputs an alarm when it detects a change in the input data distribution. It uses the output of the Estimator and may or may not use the information in memory [203].

Adaptive Sliding Windows

An important aspect of data stream mining is the construction of adaptive windows to assess the changes of data over time. The window strategies can be used for several tasks: to detect changes by using some statistical test on different sub-windows; to obtain updated statistics from recent examples and to have data to rebuild the models after data has changed [203].

The application of windowing can be done externally or embedded in the learning algorithms. For example externally the window is used to monitor the error rate of the current model and inside the learning algorithm to maintain the statistics required by the algorithm continuously updated [217].

Kifer et al. proposed [218] the Equal and Fixed size sub-windows which are characterized for comparing one reference non-sliding window of older data with a sliding window of the same size keeping the most recent data. In [219] the Equal Size Adjacent sub-windows comparing two adjacent sliding windows of the same size of recent data was presented. Gama et al. [220] with the Total Window Against Sub-window method compares the window that contains all the data with a sub-window of data from the beginning until it detects that the accuracy of the algorithm decreases. The strategy presented by Bifet and Gavaldà [217] was the algorithm ADaptive WINdowing (ADWIN) to compare all the adjacent sub-windows that result from the partition of the window containing all the data. There are also scientific works using weighted windows. In [221] the size of a window is defined by time and it is possible to assign different weights to different windows according to the importance of data.

3.3.1.4 Interpretation and Evaluation

The interpretation and evaluation of the results is also a major step. The way of conducting this phase in classical application of learning algorithm was determined by the data size as it was explained in Section 3.2.5. When the evaluation is done in data stream the main concern is how to construct an image of accuracy over time [203].

Most of the research in data stream evaluation is done with a Holdout method [222]. To understand the model performance over time, the model can be evaluated periodically. Another scheme for evaluating data stream algorithms is to interleave the test and then the train phases. Each example can be used to test the model before it is used for training and from this the accuracy can be incrementally updated [203]. This method is different, since no holdout set is necessary for testing, making the optimization of the available data. The accuracy over time is also smoother because each example will become increasingly less significant to the overall average. Nevertheless, there are also disadvantages of using this method. In fact, the time to separate and measure the training and the test phases is difficult to determine. The accuracy can also be compromised if the mistakes are done in an early stage.

It is defended [203] that in order to adequately evaluate data streams classification algorithms it is necessary to test them on very large streams and under explicit memory limits. The evaluation of the model created by training examples in a finite dataset it is done using a test set, the evaluation of data streams concerns in taking snapshots at different times during the induction of a model to see how much the model improves with further training [203].

3.3.2 Process Mining

Process mining is a recent area that is inspired by machine learning/data mining and process modeling/analysis. The objective is to discover, monitor and improve real processes by extracting knowledge from event logs [223] in information systems. Figure 24 shows the overall approach of process mining.

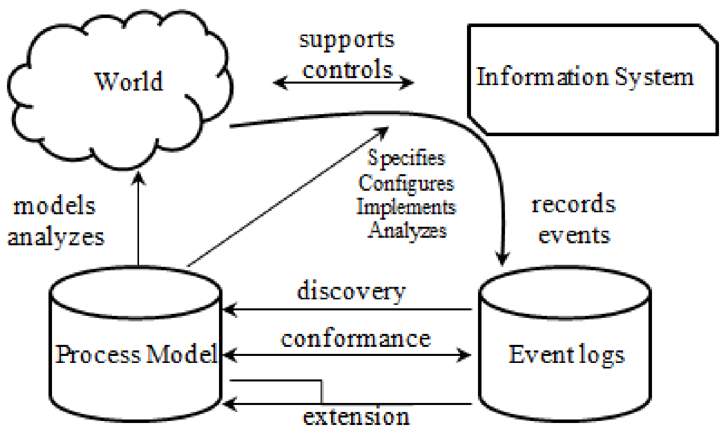


Figure 24: Approach of process mining (adapted from [223]).

Process mining aims at improving the process management by providing methodologies and tools for discovering process structures, control/data structures or organizational/social structures from event logs previously recorded [223]. Process mining techniques are typically used when no formal description of the process is available or when the quality of the existing documentation is quite low.

There are three main classes for process mining techniques based on whether there is a previously defined model and on how it is used:

- Discovery - there is not a priori model and, based on an event log, a new process model can be discovered based on low-level events. There are many techniques to automatically construct process models based on event logs [224] [225] [226].
- Conformance - in this case there is an a priori model that is compared with the event log. The discrepancies between the log and the model are analyzed and used

to detect deviations to enrich the model. Typical data mining techniques are then used to understand which data elements influence the choice generating a decision tree for each choice in the global process.

- Extension - in this case there is also an a-priori model that is extended with a new aspects and perspectives in order to enrich the model and not only to analyze it for conformance.

Several software frameworks aiming the evaluation of process mining algorithms have been developed in recent years. An example is the Eindhoven University of Technology software framework developed by Wil van der Aalst et al [223] that is available as an open source toolkit [227].

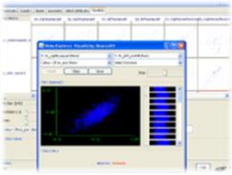
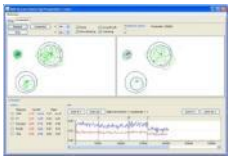
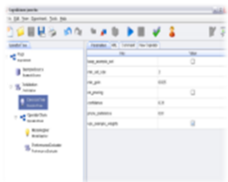
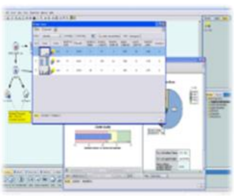
3.4 Knowledge Discovery Tools

There are several tools in which knowledge discovery techniques are implemented. Some of the tools have just a few implementations of data mining tasks; however there are others which incorporate almost every technique to perform a complete knowledge discovery analysis. It is also important to refer that for each problem and their specification there are different techniques that can be applied. Therefore, and since the KD is still an emerging science, it became imperative to create new KD tools that allow easy combination of new methods and adaptation of existing methods with low effort.

Nowadays there are instruments with different specifications as for example: if it is a commercial product or a research prototype; which are the database characteristics in terms of data model, database size and support for queries; the amount of required user interaction; if it has a stand-alone or a client/server architecture. In [228] a survey can be found of knowledge discovery tools and a feature classification scheme to review the tools that were available at that time. Later, in 2004 and 2005 King [229], Santos and Azevedo [230] presented other comparative studies of the tools. Cruz and Cortez paper [231] includes a more detailed experimental work focused on Weka [232] and R [233]. This research area is very significant today and several Internet sites contains lists and surveys of the most used tools and information on what seems to be the more adequate tool for the different tasks. Recent results on the area are presented at [234] [235].

Table 6 presents a list of the most recent tools and some characteristics offered by those applications. Several characteristics like version (V), license (L), destination (D), availability (AV) and architecture (AR) can also be found in [231].

Tools	Description
WEKA	Waikato Environment for Knowledge Analysis (WEKA) [232] is one of the oldest and one of the most used software in this field. The Weka toolkit is easy to integrate into other software products. However, to integrate different data mining

	processes into the same product based on Weka it is necessary to re-transform the data. (V) – 3.6; (L) - Public; (D) – Academic; (AV) - yes; (AR) – Stand alone
MOA 	Related to the WEKA project, MOA (Massive Online Analysis) [203] is an open source framework for data stream mining. (V) – 3; (L) - Public; (D) – Academic; (AV) - yes; (AR) – Stand alone
R 	R [233] is a system for statistical computation and graphics. It consists of a language and a run-time environment with graphics, a debugger, access to certain system functions and the ability to run programs stored in script files. The core of R is an interpreted computer language which allows branching and looping as well as modular programming using functions. It contains functionalities for a large number of statistical procedures such as linear and generalized linear models, nonlinear regression models, time series analysis, classical parametric and non-parametric tests, clustering and smoothing. There is also a large set of functions which provide a flexible graphical environment for creating various kinds of data presentations. (V) – 2.15; (L) - Public; (D) – Academic; (AV) - yes; (AR) – Stand alone
RapidMiner 	RapidMiner [236] provides solutions for data mining, text mining and data analysis. The number of operators related with data mining and visual data is high in this package. The tree-based layout with a modular concept also enables break-points and re-using building blocks. Another important aspect is concerned with the efficiency because of the layered data view concept, many data transformations are performed at run-time instead of transforming the data and storing the transformed data set. The scalability of RapidMiner has been improving. In the latest versions, algorithms were optimized for speed and the internal data handling allows the application of a large amount of data mining and learning methods directly on data stored in an external database. (V) – 1.5; (L) – Freeware/Shareware; (D) – Academic/Commercial; (AV) - yes; (AR) – Stand alone/Client-Server
IBM SPSS 	IBM SPSS™ is the new version of SPSS and a modular, tightly integrated, full-featured software comprised of Statistics Base and a range of modules which allow among others advanced Statistics, Bootstrapping, Custom Tables, Data Preparation, Decision Trees, Exact Tests, Forecasting, Missing Values, Neural Networks and Regression. (V) - 21; (L) - Commercial; (D) – Academic/Commercial; (AV) - yes; (AR) – Stand alone/Client-Server

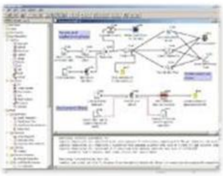
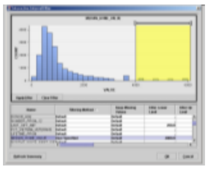
KNIME 	KNIME is a modular data exploration platform that enables the user to visually create data flows, selectively execute some or all analysis steps, and later investigates the results through interactive views on data and models. Additional plug-ins allow adding modules for text, image, and time series processing and the integration of various other open source projects, such as R and WEKA. (V) – 2.6; (L) - Freeware/Shareware; (D) – Academic; (AV) - yes; (AR) – Stand alone
Insightful Miner 	Insightful Miner deploys predictive analysis against large data sets, extracting actionable intelligence from huge data. Supports every step of the data analysis process with integrated components that handle data access, preparation, modelling and deployment tasks. (V) – 2.0; (L) - Commercial; (D) – Academic/Commercial; (AV) - yes; (AR) – Stand alone/Client-Server
SAS Enterprise Miner 	The SAS Enterprise Miner allows creating predictive and descriptive models based on large volumes of data from across the enterprise. (V) – 12.1; (L) - Commercial; (D) – Academic/Commercial; (AV) - yes; (AR) – Stand alone/Client-Server

Table 6: KD tools principal characteristics.

Nowadays many solutions are available to analyse data and construct models for classification or regression.

3.5 Knowledge Discovery Applications

Knowledge Discovery and Data Mining applications have been studied in different areas like Sciences, Economics, Health Care Management and Sports [237] [238] [239] [240] [241]. The concept of Data Mining is evolving to fields like Text Mining (classification problems with data in form of text) [242] [243] [244], Voice Mining [245] and Health-Mining [246].

3.5.1 Applications using Brain Computer Interface

EEG signals may be used to facilitate the communication between a machine and people with severe limitations. The process of EEG based control follows several phases (Figure 25). The phases can be integrated in the process of knowledge discovery.

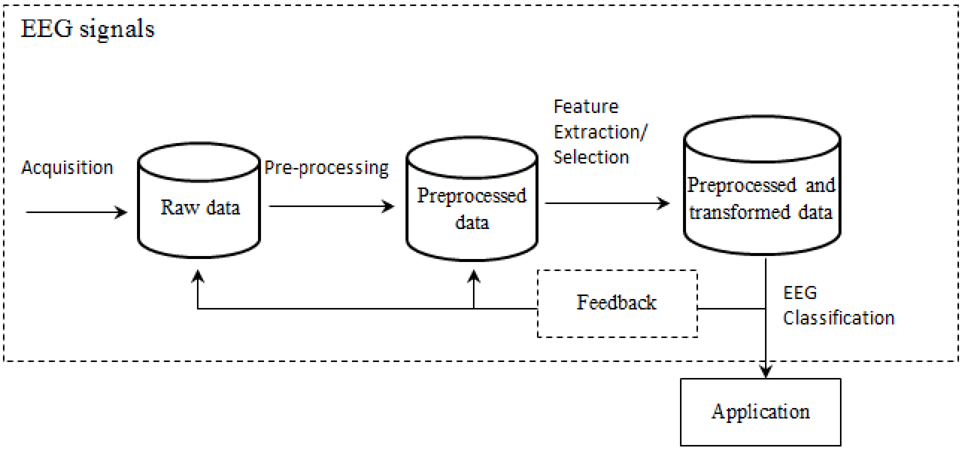


Figure 25: Phases for applying EEG signals.

3.5.1.1 EEG Data Acquisition and Data Selection

A mentioned in Section 2.1.4.5 the brain signals can be acquired with the electrodes attached to the scalp surface applying for instance the International 10-20 system.

After the data is collected, there are several solutions [247] to divide the signal into representative segments so they can be used for feature extraction. There are different approaches to do EEG segmentation [248]: separating the EEG signal into segments with the same length and adaptive segmentation which divides the signal with variable length.

3.5.1.2 EEG Pre-processing

The pre-processing phase prepares raw EEG signals into data that can be used in the next phases. The EEG signals are composed of brain activity information, reference activity information and noise. The objective is to obtain a reconstructed signal of the brain activity by trying to eliminate noise and reference signal [249].

The reference signal is important since the signal voltage measurement needs to be compared to the reference site. Typically the reference site is chosen in a location where the activity is almost zero. An EEG voltage signal represents the difference between the voltages at two electrodes. The representation of the EEG channels is called as a *montage* [250]. This can be done in different ways [249]:

- Bipolar montage is characterized by the difference between two adjacent electrodes. Each channel is represented by the names of the electrodes (for example the channel “F3-C3” represents the voltage difference between F3 and C3, and the channel “C3-P3” represents the voltage difference between C3 and P3). The entire montage consists of a series of these channels.
- Common referential montage where each channel represents the difference between a certain electrode and a reference electrode. The position for the reference electrode is often chosen in midline positions to avoid amplifying the signal in one

hemisphere versus the other. Another reference place could be the earlobes or mastoids.

- Average reference montage is composed of the outputs of all of the amplifiers which are summed and averaged, and this averaged signal is used as the common reference for each channel.
- Laplacian montage is characterized by having to calculate for each electrode location the second derivative of the instantaneous spatial voltage distribution. Each channel represents the difference between an electrode and a weighted average of the surrounding electrodes.

Noise and artefacts are elements that can distort the real values of the brain activity. The noise can be introduced by electromagnetic fields of neighbour devices or even by static electricity signal [249]. Filters can be applied to reduce the noise in EEG signals. The artefacts are introduced in the brain signals by involuntary movements of the body as for example the eyes blink. To remove this kind of misleads there are several proposed processes: filtering; artefact rejection; artefact subtraction; adaptive filtering and blind source separation.

Time and Frequency Domains

Fourier analysis [251] can be used to decompose a signal into its frequency components. Fourier analysis allows obtaining information that cannot be easily visible in the time domain [248]. The basic functions of the Fourier transform are sinusoidal functions or complex exponential signals. Equation 6 defines the Fourier transform of a continuous real-time and aperiodic signal *x(t)*:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-i\omega t} dt \qquad \textbf{(Eq 6)}$$

where $\omega = 2\pi f$ is the angular frequency in radians / s.

The inverse transform allows changing a signal from the frequency domain to time domain as in Equation 7:

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X(\omega) e^{i\omega \cdot t} d\omega \qquad \textbf{(Eq 7)}$$

The natural process of analysing EEG using computational methods is applying sampling and obtaining the discrete time Fourier transform of a discrete time signal *x(n)*:

$$X\left(e^{i\omega}\right) = \sum_{n=-\infty}^{+\infty} x(n) e^{-i\omega n} \qquad \textbf{(Eq 8)}$$

If ω is sampled on the unit circle, then the discrete Fourier transform of N length sequence *x(n)* is:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-i\frac{2\pi}{N}kn} \quad \textbf{(Eq 9)}$$

where $\omega_k = \frac{2\pi}{N}k$, $n = 0, 1,\ldots,N\text{-}1$ and $k = 0, 1,\ldots,N\text{-}1$. N is the number of spectral samples in one period of the spectrum $X(e^{i\omega})$. The inverse discrete Fourier transform equation is:

$$X(n) = \frac{1}{N} \sum_{n=0}^{N-1} x(k) e^{i\frac{2\pi}{N}kn} \quad \textbf{(Eq 10)}$$

where $n = 0, 1,\ldots,N\text{-}1$ and $k = 0, 1,\ldots,N\text{-}1$.

Usually, the Fast Fourier Transform (FFT) algorithm [252] is used to compute the discrete Fourier transform reducing the complexity from N^2 to $N*log(N)$.

Segmentation

The data segmentation is the process of dividing the signal into representative segments in order to extract features from each segment. There are two main approaches to perform EEG data segmentation [247] [253]: fixed-length segmentation and adaptive segmentation.

The first option separates the EEG signal into segments of the same length and is characterized by having four phases. The EEG signal is divided preliminary into equal minimal segments, next each segment is considered as a set of features, then the main segments are assigned to a class and finally the boundaries between the segments belonging to the surface same class are erased.

The second option can be based on the estimation of the level of similarity of an initial fixed EEG interval with an EEG interval of the same duration viewed through the time window running along the EEG recording. If the window runs over a segment boundary the similarity index drops revealing the transition to the following segment [247] [253].

The segmentation in the time domain is equivalent to multiplication of the complete EEG signal with a finite rectangular window [248]. Applying windowing it is possible to reduce the waves and tends to reduce sharp variations of the discrete Fourier transform. There are several solutions for windowing, some of which are presented in the next equations and in [248].

- Rectangular (or Dirichlet)

$$W_R(n) = \begin{cases} 1 & |n| < N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq 11)}$$

- Bartlett

$$W_B(n) = \begin{cases} \dfrac{N-|n|}{N} & |n| < N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq 12)}$$

- Gaussian

$$W_G(n) = \begin{cases} e^{-\frac{1}{2}\left(\frac{n-\frac{N-1}{2}}{\frac{\sigma(N-1)}{2}}\right)^2} & |n| < N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq 13)}$$

where σ is equal or less than 0.5.

- Hamming

$$W_{Ham}(n) = \begin{cases} 0.54 - 0.46\cos\left(\frac{2\pi|n|}{N-1}\right) & |n| < N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq 14)}$$

- Hanning

$$W_{Hann}(n) = \begin{cases} 0.5 - 0.5\cos\left(\frac{2\pi|n|}{N-1}\right) & |n| < N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq 15)}$$

The selection of the most suitable window depends on the application objectives and requires tests and evaluations of errors.

3.5.1.3 Feature Extraction and Selection

Feature extraction, for subsequent classification, can be performed in the time domain, frequency domain or time-frequency domain [254] [108] [249].

In every study of EEG signals feature extraction analysis is presented regardless the division in time or frequency domain. Features that can be extracted from the time domain are:

- Mean – normally the mean is constant when the time is not too short, because of the EEG potential being on the order of microvolts. When an event occurs this value can also change showing a drift in the mean of the signal. The mathematical equation is given by Equation 16 where x_i is the signal value for $i = 1,\ldots,N$ and N the number of the data points:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad \textbf{(Eq 16)}$$

- Standard Deviation – the variation of data can be obtained with this measure. If the homogeneity changes probably the events also may be changed. Equation 17 gives this value:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad \textbf{(Eq 17)}$$

- Maximum peak value – it is obtain by the maximum of the absolute value of the segment *k* (Equation 18):

$$x_k = \max(x_i) \tag{Eq 18}$$

- Skewness – This value can be interpreted as the symmetry deviation of a normal distribution. With this measure it is possible to compare the symmetry of EEG waveforms to the obtained baseline, for instance when an individual is a sleep. The skewness can be calculated by the Equation 19:

$$s_k = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^3}{s^3} \tag{Eq 19}$$

  Positive values reveal a positive asymmetry, negative values a negative asymmetry and the zero value means that the distribution is symmetric.

- Kurtosis – With this value it is possible to know the flatness of the distribution.

$$k_m = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^4}{s^4} - 3 \tag{Eq 20}$$

  Positive value reveals a leptokurtic distribution, negative value a platykurtic and the zero value means that the distribution is mesokurtic.

- Cross correlation – This measure determines the similarity between two signals. Equation 21 gives the cross correlation between x_i and y_i with the delay d and for $i = 1,\ldots,N$.

$$r_{xy}^{d} = \frac{\sum_{i=1}^{N}\left[(x_i - \bar{x})\times(y_{i-d} - \bar{y})\right]}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{N}(y_{i-d} - \bar{y})^2}} \tag{Eq 21}$$

- Hjorth parameters – Hjorth [255] presented three parameters to characterize the EEG signals in terms of amplitude, time scale and complexity [249]. These parameters can discriminate between mental states. The parameters are:
  - Activity – it is a measure of the mean power of the signal. It is measured using the standard deviation of the signal:

$$h_1 = s^2 \tag{Eq 22}$$

  - Mobility – it represents the mean frequency in the signal. This measure can be calculated as the ratio of the standard deviation of the slope (s_d) and the standard deviation of the signal, as in Equation 23:

$$h_2 = \frac{s_d}{s} \quad \textbf{(Eq 23)}$$

- Complexity – the objective of with this measure it is to capture the deviation from the sine wave (the softest possible curve). It is expressed as the number of the standard slopes actually seen in the signal during the average time required for one standard amplitude deviation. Equation 24 allows to calculate the complexity:

$$h_3 = \frac{s_{dd}}{s} \quad \textbf{(Eq 24)}$$

where s_{dd} is the standard deviation of the second derivative of the EEG signal.

Frequency domain can be another method to transform the brain waves and to extract features from these signals. The next features characterize the power of the brain in several frequency bands.

- Auto-regressive coefficients – the objective is to present each sample of the signal as a linear combination of previous samples in addition to white noise. The coefficients are used as features.

$$x_k = -\sum_{i=1}^{N} a_i x_{k-i} + \varepsilon_k \quad \textbf{(Eq 25)}$$

  where a_i are the auto-regressive coefficients, ε_k is the white noise and N the order of the AR model.

- Power spectrum density (PSD) – by using power instead of voltage as a function of frequency it is possible to calculate the power spectrum density of a random signal x_i using the Equation 26 (Fourier transform of the autocorrelation function):

$$PSD = \left| \sum_{i=1}^{N} x_i e^{\frac{-j2\pi ki}{N}} \right|^2 \quad \textbf{(Eq 26)}$$

  where $k=1, 2, \ldots, N$ and x_i represents the discrete samples of EEG.

- Band power – The power spectrum density can be applied to each band in order to extract features.
- Asymmetric ratio PSD – The value can be obtained by the power spectrum density and it is useful when the mental tasks have inter-hemispheric differences. The ratio can be obtained by the equation:

$$AS_{PSD} = \left[\frac{PSD_L - PSD_R}{PSD_L + PSD_R} \right] \quad \textbf{(Eq 27)}$$

  where PSD_L and PSD_R are the power spectrum densities in opposite hemispheres.

The features in Time-Frequency domain characterize how spectrum power varies over time.

- Short Time Fourier Transform – by dividing the input signal into segments, the signal can be assumed as stationary, then it is applied the Fourier transform. For that reason the definition of Short Time Fourier transform is the application of the Fourier transform to these segments. The discrete Short Time Fourier Transform of a signal x_i at time i is obtained by the Equation 28:

$$STFT(x_{i,k}) = \sum_{m=1}^{N} x_{i+m} w(m) e^{\frac{-j2\pi(k-1)m}{N}} \quad \textbf{(Eq 28)}$$

  where $k= 1,\ldots,N$ represents the frequencies variables and $w(m)$ is the window function.

- Wavelet Transform – the wavelet transform uses wide and narrow windows for slow and fast frequencies respectively, conducting to an optimal time-frequency resolution in all frequencies ranges.

$$WT(x_t, a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x_t \Psi^*_{a,b}\left(\frac{t-b}{a}\right) dt \quad \textbf{(Eq 29)}$$

  where a ($a \neq 0$) and b are real values representing the scale and the translation parameters; t is the time and Ψ^* is the complex conjugate of the mother wavelet function.

- Discrete Wavelet Transform – when dealing with digitalized signals, the discrete wavelet transform can be applied where the coefficients $a = 2j$ and $b = k^2j$ are discretized (j and k are integers values).

$$DWT(x_t, a, b) = d_{j,k} \approx \int_{-\infty}^{+\infty} x_t \Psi^*_{j,k}(t) dt \quad \textbf{(Eq 30)}$$

  where $d_{j,k}$ are the WT coefficients sampled at discrete points j and k.

After extracting the features that characterize the EEG signals, it is possible to reduce their number by selecting them without significant loss of information. There are several methods to do feature selection such as R-squared, filters or wrapper methods [256]. For example McFarland and Wolpaw [257] study the effects of feature selection in a BCI application to control cursor movements. The applied method was the R-squared to the spectral features of EEG sensorimotor rhythms. Shroder et al. [258] presented a wrapper method for feature selection and they concluded that the feature selection depends of the subjects and the experimental paradigm. Peterson et al. [259] studied a modification of the wrapper method for feature selection based on support vector machines.

3.5.1.4 EEG Classification

The techniques presented in Section 3.2.4.2 are used in the EEG classification phase. There are several surveys available [260] [247] [112] where descriptions of applications of the classification algorithms are presented [261].

Neural networks applications can be found in several works. Subasi et al. [262] use neural networks and logistic regression [263] for the classification of patients into two groups such as epileptic and non-epileptic. The EEG classification was used for the diagnosis of Alzheimer's disease in [264]. Another application was the control of 2D movements of a robotic arm [265] and intelligent wheelchairs [42] [39].

3.5.2 Applications in the Health Area

In the context of this thesis it is also interesting to investigate the recent applications of Knowledge Discovery for classifying patients or even what has been done in the health area. Some interesting data mining applications can be found. For instance, Cheng et al. [266] applied clustering and association to analysis disease clusters of chronic senility to enhance quality of health care service. Ben et al. [246] presents a Decision Support System with the objective of controlling the adequacy of hospitalization and therapies, determining the effective use of standard guidelines and identifying the best ones from the medical practice. Two applications can be found at [267] using data mining techniques. The first example is a clinical application derived from operational data where a predictive scoring model enables the assessment of re-hospitalization risk for patients at discharge time. The second application is on medical material supply chain management using a dataset from the military medical logistics warehouse. In [268] the objective was to apply rough set concepts and the reduction algorithm to search for patterns specific/sensitive to thrombosis disease. Rao [269] presents the description of the patent of a data mining framework which includes a data miner for medical information from a computerized patient record (CPR) based on domain-specific knowledge contained in a knowledge base.

Several applications have already been made in patient mining, including applications to recognize disease evolution. In [270] data mining algorithms were used to analyse the effectiveness of immunotherapy treatment and to understand the prominent parameters and their interactions and then build a patient recognition model for prediction of treatment outcomes.

Beside this there is not a developed theory and applications to automatically classify patients and their observed characteristics. In terms of the classification of users of intelligent wheelchairs and how to assign the best interface to each user so that he may better manoeuvre an IW. Although it is possible to obtain information by the medical diagnosis, the same disease such as cerebral palsy has different degrees and what suits one patient can be completely different for other patient with the same diagnosis.

Therefore, it is important to establish a medical classification and this attribute can be used to facilitate the phase of creation of the patient model. The following section presents some definitions of the handicapped individual levels.

3.5.3 Users and Patients Classification

The potential users of IW are handicapped individuals and patients with distinct disabilities like Thrombosis, Stroke, Cerebral Palsy, Parkinson, Alzheimer and Multiple Sclerosis.

First there are diverse levels of individual constrains. The World Health Organization [271] [272] provided definitions and differences between the concepts of Impairment, Disability and Handicap:

- Impairment: Any loss or abnormality of psychological, physiological or anatomical structure or function.
- Disability: Any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being.
- Handicap: A disadvantage for a given individual, resulting from an impairment or disability, that limits or prevents the fulfilment of a role that is normal, depending on age, sex, social and cultural factors, for that individual.

To better understand the symptoms of the potential users, the following list describes the principal characteristics of the diseases that are expected to be present in the IW users.

- A Thrombosis is the formation of a clot in the blood that either blocks, or partially blocks a blood vessel. The thrombus may lead to infarction or death of tissue, due to a blocked blood supply [273].
- A Stroke is the sudden death of brain cells in a localized area due to inadequate blood flow. A stroke can be originated by a thrombosis [274].
- Cerebral Palsy (CP) is the term used for a group of nonprogressive disorders of movement and posture caused by abnormal development of, or damage to, motor control centers of the brain. CP is caused by events before, during or after birth [272]. The abnormalities of muscle control that define CP are often accompanied by other neurological and physical abnormalities [275].
- Parkinson's disease is a brain disorder. It occurs when certain nerve cells (neurons) in a part of the brain called the *substantia nigra* die or become impaired. Normally, these cells produce a vital chemical known as dopamine. Dopamine allows smooth, coordinated function of the body's muscles and movement. When approximately 80% of the dopamine-producing cells are damaged, the symptoms of Parkinson's disease appear [276].
- Alzheimer's disease (AD) is the most common form of dementia, a neurologic disease characterized by loss of mental ability severe enough to interfere with normal

activities of daily living, lasting at least six months, and not present from birth. AD usually occurs in old age, and is marked by a decline in cognitive functions such as remembering, reasoning, and planning [277].

- Multiple Sclerosis (MS) is a chronic autoimmune disorder affecting movement, sensation, and bodily functions. It is caused by destruction of the myelin insulation covering nerve fibers (neurons) in the central nervous system (brain and spinal cord). The consequences are muscle weakness, causing difficulty in walking, loss of coordination or balance , numbness or other abnormal sensations and visual disturbances, including blurred or double vision [278].

In particular, the group of patients with cerebral palsy is a very challenging one because there are very different cases even though the possible classifications within the same degrees of severity. In the areas of Occupational Therapy and Physiotherapy there are several studies with adults suffering from cerebral palsy and the primary limitations in the daily activities are in self-care and mobility [279] [280] [281]. Palisano et al. [282] presented a study referring the reduced number of children (around 10%) with age between four and twelve years old, suffering from cerebral palsy could drive an electric wheelchair in an independent way.

The problems of mobility are the most described [283] and are considered of extreme importance by young adults with cerebral palsy. Andersson and Mattsson [284] show that adults without learning difficulties could not move autonomous and independently in the community as desired. The assistive technologies are defined as any product, instrument, equipment or adapted technology specially planned to improve the functional levels of the individual with deficiency. With these products the mobility problems can be minimized. The electric wheelchairs are assistive technologies and the number of manufacturers that produce different kind of wheelchairs is increasing [285] [286] [287].

In order to use an electric wheelchair there are physical and cognitive demands which not everyone has. In a study by Fehr, Langbein and Skaar [288] it is showed that around 40% of people that desired to have an electric wheelchair could not have one because of their physical and cognitive constraints which make driving the wheelchair, in a safe manner, almost impossible.

However, it was demonstrated in a study conducted by Montesano et al. [289], with a sample composed of individuals suffering from cerebral palsy and other cognitive constraints, that it was possible to drive an intelligent wheelchair, in challenging environments, in a safe manner, after a period of training. Even the performance of children could improve after a training phase using for example an appropriate simulator [290].

In conclusion, there are several medical problems which bring severe limitations to the human being, not only at more advanced age, but also at young age. Most of these disabilities and medical problems may have very distinct symptoms for individual with the some type of illness. Thus, although the type of disability may be an obvious input for adapting the wheelchair to the patient, knowing only the kind of disability is not enough, to fully characterise the patient and configure an appropriate IW interface for him. Appropriate knowledge extraction methods using data from the patient interaction with the wheelchair are needed in order to be able to fully adapt the interface to the patient.

3.6 Conclusions

This chapter described the standards for extracting knowledge from data. The phases in knowledge discovery, including data selection, pre-processing, transformation, data mining, interpretation and evaluation were also presented. Emphasis was given to classification techniques and cluster analysis algorithms since these are appropriate for developing the intended patient classification module. Some knowledge discovery software tools were also described along with applications of knowledge discovery with emphasis on the area of users and patients classification.

The standards, the algorithms and tools described in this chapter serve as a source of inspiration for projecting and implementing the Intelligent Wheelchair patient classification application and definition of the best interface and command language. This application will enable a simple automatic selection, configuration and parameterization of the IW user interface.

Based on the state-of-the art presented in the previous two chapters, the next chapter contains the methodologies used for automatically extracting users' profiles and adapted interfaces.

Chapter 4

4. Extraction of User Profiles and Adapted Interfaces

Scientific research allowed the evolution and development of many technologies that are nowadays used in everyday life. In particular, innovations in the field of assistive technologies enabled increased autonomy and independence for human beings that, for some reason, have some kind of disability. Intelligent wheelchairs are an obvious application of the scientific work developed in the last decades in this area. Moreover, these assistive technologies still are object of research and the interaction between them and the user remains an open research problem. The creation of instruments to study these interactions in a safe manner leads to the use of simulators. These simulators allow the study and analysis of the assistive methodologies and users' performance. Another component of study comes from multimodal data analysis integrating data from different sources. Finally, the interaction between the Human and the IW is an important component to take into consideration. The users' opinions should also be integrated in the development process of the instruments which are to serve and fulfil a human necessity.

The methods implemented in this work allowed answering several questions about the usability of an intelligent wheelchair that can be commanded via a multimodal interface. Another issue is related with the creation of users' profiles in order to automatically adjust the best way of driving the intelligent wheelchair. Users' classification demands data of distinct sources such as voice, physical movements like head or facial expressions or data taken from using the usual joystick that is common in electric wheelchairs. However, gathering and analysing this type of data is still an open research problem. In order to face this problem, new multimodal data gathering and analysis methodologies were developed enabling to build a complete data gathering and data analysis system for intelligent wheelchair user profiling and classification.

This chapter describes the methodologies developed to answer the previously presented research questions. Initially, all the functionalities intended for the IntellWheels multimodal interface are presented. This multimodal interface was created with the objective of being flexible, with several input devices already integrated and much more to be easily added. Moreover, the flexibility concept means that it is possible to associate any sequence of the available inputs to any possible command (action) in order to drive the IW.

Although the development of the IntellWheels project had, as its primary objective, the integration of the developed components into a real IW, it was also important to keep these components compatible with IntellWheels simulator, as this could facilitate development tests, including tests with real IW users. Therefore, the *IntellSim* IW simulator is presented, which is an evolution of the previous simulator that was described in Section 2.4.3. In order to turn it into a realistic 3D simulator, featuring distinct IW driving modes and presenting realistic scenarios for performing meaningful experiments, a serious game for teaching IW driving abilities was developed.

The evolution of the simulator was justified with experimental work that is presented in the Section 5.1.1. In order to enhance user IW controllability when driving the IW using the joystick, three different methods were developed and evaluated; this work is presented in Section 4.4.1.1.

The developed data gathering system is also presented along with all the modules of the data analysis system. The chapter also includes formal definition of the used concepts in order to enable a better understanding of the global system developed. In order to provide a formalization of the developed concepts, the definitions of input, input device, modality, input sequence, command and command language are provided in this section together with some meaningful examples to illustrate the definitions.

Summarizing, this chapter presents the research approach with emphasis on the work performed for automatic extraction of user profiles and for adapting the IW interface to a specific user in a fast and efficient way.

4.1 System Architecture

The IntellWheels system architecture that enabled to conduct the experiments of user profiling, wheelchair control and patient classification is presented in Figure 26. The system is composed by eight main modules and enables a therapist to have full control of all the IW adaptation process.

The core of the system is the new IntellWheels multimodal interface that enables the patient to fully control real and simulated Intelligent Wheelchairs, using multimodal inputs, including pre-defined input sequences that may be freely associated with any of the available outputs (wheelchair actions). The input devices may be freely connected to this multimodal interface and include inputs using voice, head movements, traditional joystick, gamepad, facial expressions and thoughts (through a brain computer interface).

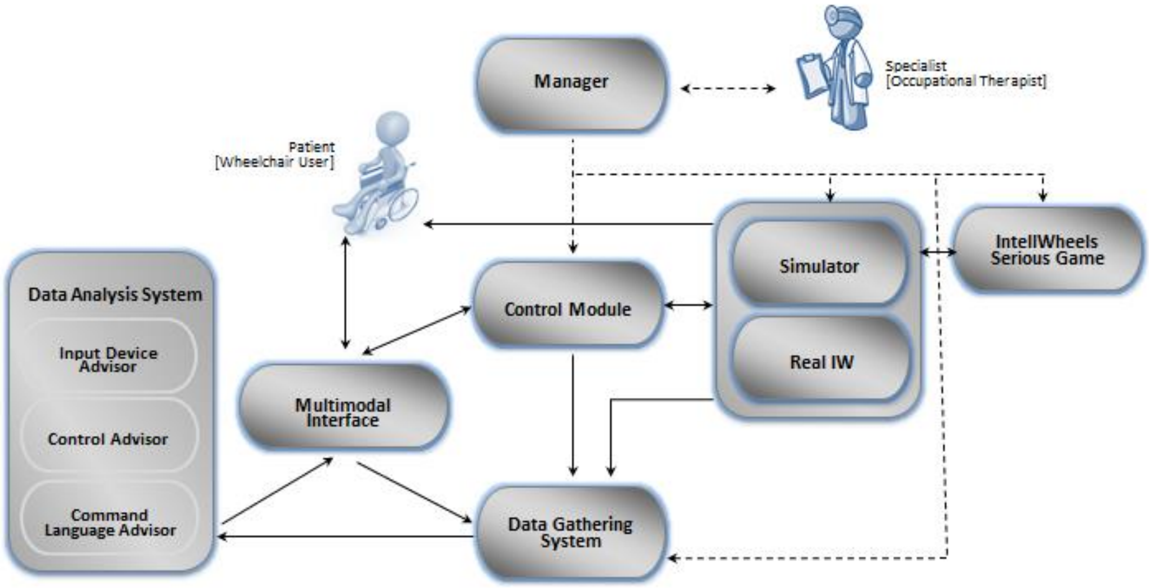


Figure 26: IntellWheels system architecture.

The multimodal interface is connected to a control module that is able to receive high-level or medium level commands from the multimodal interface and control a real or simulated wheelchair making it perform the actions corresponding to those commands (such as go front, turn right, follow right wall, stop, among many others). The control module is also responsible for providing a shared control mode that enables users with disabilities to control the wheelchair using intentions without the need of performing fine-tuned movements/inputs.

The control module may control the real IW prototype previously described but also, in exactly the same way, the simulated intelligent wheelchair in the context of the new simulator developed in this project. The simulator was built using Unreal Tournament 2004 and USARSim 3.1.3 together with a realistic scenario developed with Unreal 2004 Editor. This 3D scenario is a very realistic model of the APPC cerebral palsy institution facilities, thus enabling the development of experiments, in a simulated mode, in a scenario very similar to the one the patients were used to.

In order to be able to develop and conduct meaningful experiments, a serious game for intelligent wheelchair teaching and testing was built. This game was developed using Processing [291]. The game permits the definition of circuits and the placement of markers (balls and stars) that must be collected by the user in order to gain points. It also enables gathering other performance measures such as the time and the precision of the trajectory of the users performing the circuit.

In order to be able to extract user profiles and adapt the user interface to the users' profiles several other applications were developed. A first one consists on a complete data gathering system that is able to gather the data available on: the multimodal interface; control module; simulated wheelchair; real wheelchair and serious game, and then synchronize all this data and freely select the values to record in appropriate files in order to be further analyzed by the data analysis applications. A user profiling application was also created in this context, in order to be able to conduct controlled experiments with each user and to analyze their capabilities of performing each type of possible input in each of the available input devices.

Based on the user profiling and associated data gathering system, a data analysis system was developed enabling the analysis of users capabilities when performing each type of input and when driving the IW with different input combinations and using distinct control modes (normal and shared with distinct levels of handicap). Beyond data analysis, this module is able to advise, in a simple manner, the best control mode for each user and to specify a command language adequate for each user.

A manager module was also developed in order to be able to perform a large set of experiments using the developed user profile extraction methodology and the set of implemented applications. This manager allows to launch all the applications, perform user profiling tests, define the scenario to be used, the circuit to be performed, the control modes to be tested and the data to be gathered and analyzed.

4.2 IntellWheels Multimodal Interface

The problem of designing specific interfaces for individuals with severe physical disabilities presents many challenges to which many authors have tried to answer.

There are several publications in the literature describing projects related to this issue, which tried different approaches to implement viable solutions to address the problem of developing appropriate interfaces enabling disabled individuals to drive intelligent wheelchairs [91] [38] [92]. Nevertheless, the vast majority of these projects present limited solutions concerning the accessibility and recognition methods offered to the user to drive a particular wheelchair. It is common to find solutions providing only voice recognition, while others focus merely on facial expressions recognition. Since physical disabilities are very wide in kind and degree, and thus very specific to each individual, it becomes important to provide the largest possible number of input methods in order to cover the largest possible number of individuals with different characteristics.

Currently, the multimodal interface offers five input methods based on distinct signal recognition methods: joystick signal recognition, speech recognition, head movements recognition, the use of a generic gamepad and facial expressions recognition using a Brain Computer Interface. In addition, the system architecture makes the interface extensible, enabling the addition of new devices and recognition methods in a transparent and easy way[1]. The multimodal interface also presents a flexible paradigm that allows the user (or an assistant) to define the input sequences assigned to each action, allowing an easy and optimized configuration of the interface for each user.

4.2.1 Input Sequence

To understand the adopted interaction style it is important to clarify the concept of input sequence used in the multimodal interface.

Definition 5: An **Input Sequence** (*S*) is a tuple of inputs ($I_k, k \in \mathrm{N}$). The space of sequences *S* belongs to $I^N = \underbrace{I \times I \times ... \times I}_{N\ times}$. An input sequence S_i can be formalized as $I^{(i,1)}$ $I^{(i,2)}$ $I^{(i,3)}$...$I^{(i,Ni)}$, where each $I^{(i,N_i)} \in \{I_1, I_2, ..., I_k\}$.

Example 5: Say "Go", then blink the left eye and then push button 3 is an example of an input sequence.

Some multimodal systems combine different input modalities in order to trigger multimodal commands. Although the merging of different inputs can provide a very attractive way to perform human machine interaction, if it is not well adapted to the specific task and user it can harm more than help people with physical disabilities.

The objective of the IntellWheels multimodal interface is to provide the user with a large variety of different possible inputs that can be expressed by individuals with different physical capabilities. Thus, a simple mechanism is proposed in order to allow the user to interact with the multimodal interface. It consists on the interpretation of the user inputs in a sequential manner. Since this is a system that aims to be used by disabled people, avoiding errors is of extreme importance. For example, if a user associates a voice input which consists of pronouncing the word "Go" to the output action that makes the wheelchair start moving forward, then, this might originate accidents in the way that a false recognition by the speech recognition module would originate an undesired event. Instead, the multimodal interface allows the possibility of creating input sequences, composed by simple inputs that may be easily performed by the user or even to choose other word or input combinations, easily detected by the interface, to trigger the desired output after verifying that the system recognition percentage threshold is met.

[1] Recently it was implemented a virtual joystick that can be integrated in a smartphone, however this modality was not object of study.

Figure 27 presents a graphical illustration of the use of an input sequence to trigger an IW command. It consists of pronouncing the expression “Say something”, followed by pressing button 3 on the gamepad, and finally blinking the right eye.

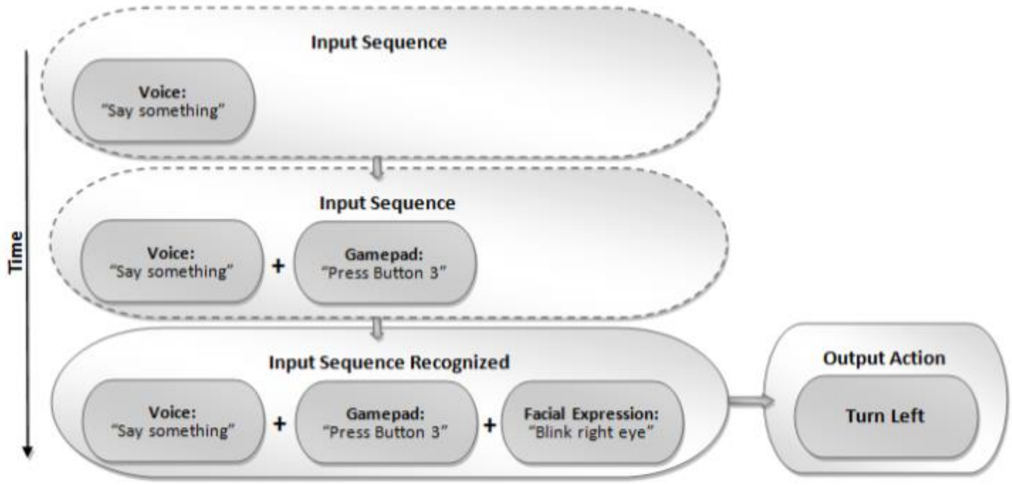


Figure 27: Concept of input sequence.

4.2.2 User and Multimodal Interface Interactions

This section presents the main interactions between the user and the IntellWheels Multimodal Interface. They were grouped in four different main modules:

- Navigation Mode - This module uses previously saved associations and user inputs to derive the output actions during IW navigation. This represents the most important feature of the multimodal interface, which is to request the execution of a certain action, via input sequence, using a previously created association.
- Sequence Manager - This module is related to the management of the saved associations between input sequences and output actions (Figure 28). The user can create a new association by selecting the inputs and the desired sequence (which can be done by actually executing the input sequence) and map it to the desired IW action. It is also possible to consult associations created in the past, and to change or delete them.

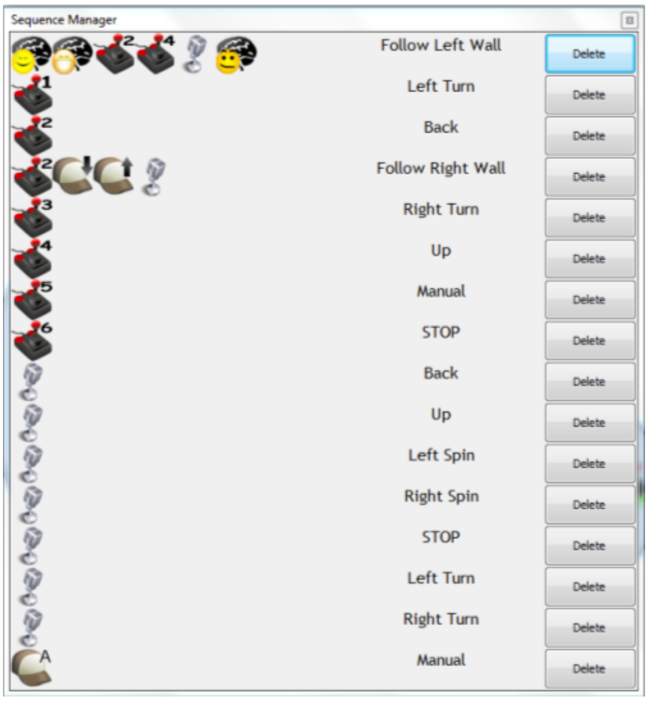


Figure 28: Sequence Manager with a command language.

- Device Manager - This module provides the user with a small viewer that which shows information regarding the state of basic input devices such as information about the wiimote motion sensors, battery level and active gamepad buttons (Figure 29). This viewer is intended to test the correct functioning of the input devices. The user can also adjust some minor configurations for these devices, to attain an optimized experience while using the multimodal interface. Configurations may consist of defining a minimum speech recognition trust-level and maximum speed for the gamepad joysticks.

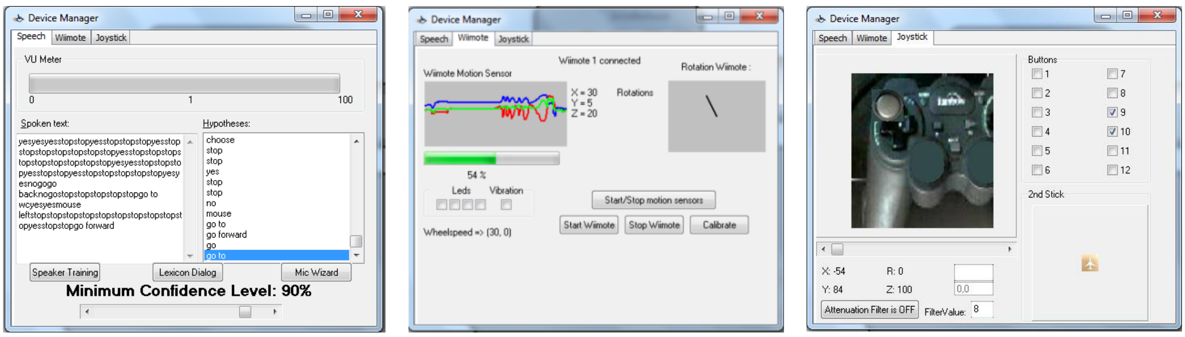


Figure 29: Device manager with information about the basic input devices.

- User Profiling - This module handles the interactions related to the creation or update of a user profile. During this process, the user can separately train the use of the basic input modalities offered by the IntellWheels multimodal interface. A more detailed specification of the user profiling module is presented in Sections 4.5.3.2 and 5.1.4.

One of the main goals of this system architecture proposal is to provide the user with full control of the interface.

In order to fully define the multimodal interface it is necessary to formalize the concepts of command and command language.

Definition 6: A **Command** (*C*) is an action that may be executed by the wheelchair and it is triggered by a given input sequence. A single command may be associated to each input sequence.

Example 6: The actions “Turn left”, “Turn right” of the IW may be two different commands in this context.

Definition 7: An **Association** $A = (S, C)$ between an Input Sequence (*S*) and a Command (*C*) is a relation between an Input Sequence and a Command.

Example 7: The sequence S_1 (Say “Go” + Blink Left Eye) → C_5 (“Turn Left”) is a possible input sequence to command association (example: $A_7 = (S_1,C_5)$).

Definition 8: A **Command Language** (*CL*) is a set of associations of input sequences to commands allowing a user to drive the IW with the available actions and inputs. Formally a command language is designated as a function that for each input sequence relates it to exactly one command

$$\begin{aligned} CL : S &\rightarrow C \\ S_{\mathrm{i}} &\mapsto C_{\mathrm{j}} \end{aligned} \qquad \textbf{(Eq 31)}$$

where $i \in \{1,...,n_S\}$, $j \in \{1,...,n_C\}$, n_S is the number of available input sequences and n_C is the number of available commands.

Example 8: Figure 28 presents very simple command language associating sixteen input sequences with eleven distinct commands.

4.2.3 IMI Requirements

Output Actions

Since the control of the IW is performed in the Control application and has itself the role of establishing the connection with the wheelchair robot and sending the low-level orders directly to the motors, and the Multimodal interface is a distinct application, a protocol was created for these two applications to communicate and exchange information between them (Figure 30).

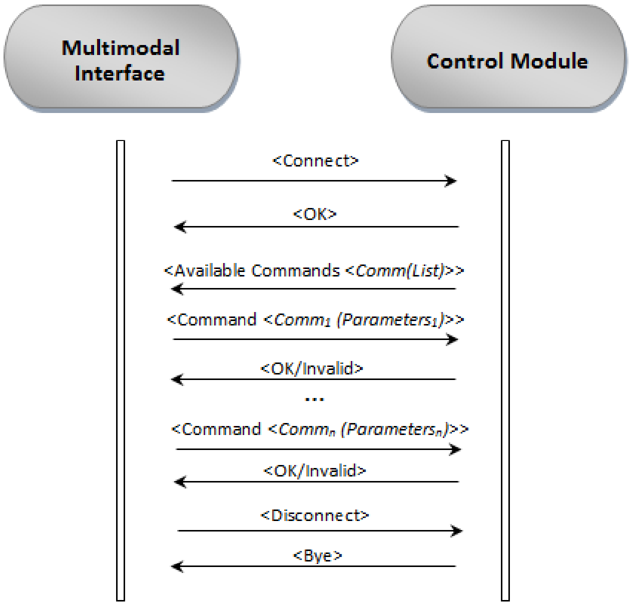


Figure 30: Communication protocol between the multimodal interface and the control.

Thus, the control module should notify the multimodal interface with the available commands (e.g. go forward, left turn, manual mode) as illustrated in Figure 30.

An abstract structure for defining a command was created to make the multimodal interface independent and unaware of the context of its use. This enables to use the multimodal interface to control other devices such as a television or an electronic Boccia ramp. The interface just receives the available commands on the connected devices and enables the user to freely define the input sequences used to trigger each of the commands.

Input Devices

Since a multimodal interface is a human-machine interface which combines several input modalities between the user and the machine, one of the requirements of the IMI is the ability to accept inputs from a larger number of input devices. Therefore, the interface should be aware of the available input modalities, by having a core component capable of interpreting the inputs sent by all the input devices, in a generic and abstract way. These inputs should have their origin in internal (joystick, speech recognition, head movements) or external input devices, such as a brain computer interface (Figure 31).

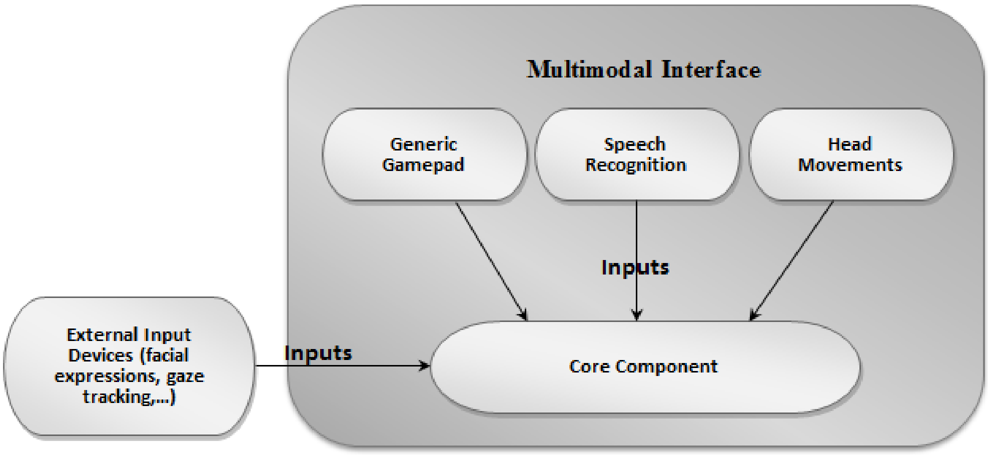


Figure 31: Input Devices and the IMI.

To allow the interaction between the IMI and external input devices, a simple communication protocol was created. This protocol is presented in Section 4.2.5.2.

Custom Configuration

One of the most important goals of the IMI is to allow the end user to easily define the associations between a set of input sequences and their corresponding output commands. Therefore, the IMI should provide a flexible way of creating customized input sequences, composed by multiple inputs, of possibly distinct input devices, that could be freely associated to each of available commands (Figure 32). An important feature of the system is that the same command may be triggered by several distinct input sequences. This may be very useful for increasing the system safety, for example associating several input sequences for the stop command.

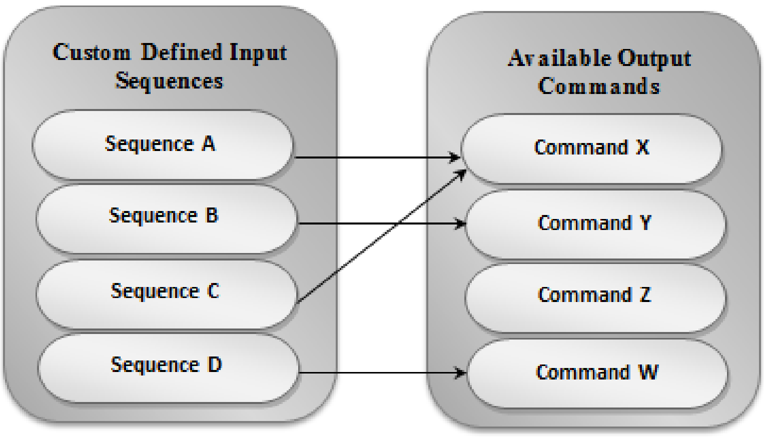


Figure 32: Associations between input sequences and output commands.

Interface Actions

To offer the user a complete multimodal experience while using the IMI, another feature was included in the IMI. Using the previously described features, it is also possible to associate input sequences to commands that are fully related with the multimodal interface itself. These actions may consist, for example, of moving the mouse pointer using head movements, or consulting the existing associations by pronouncing a voice command. The goal is to avoid the WIMP interaction style while performing the Graphical User Interface (GUI) related operations replacing it with the multimodal style of interaction. In spite of being of a distinct type, interface actions had the same abstract structure created for the output actions. Associations related to interface actions may be saved to the system database.

Database

To avoid the users having to configure the interface according to their preferences each time the IMI is used, all the information regarding the output commands, custom input sequences and associations should be saved in a database. This external database should be available and accessible by the IMI at the beginning of the execution and during the runtime process. Therefore, every time the IMI is launched, all the past information should be loaded to become available during each execution (Figure 33).

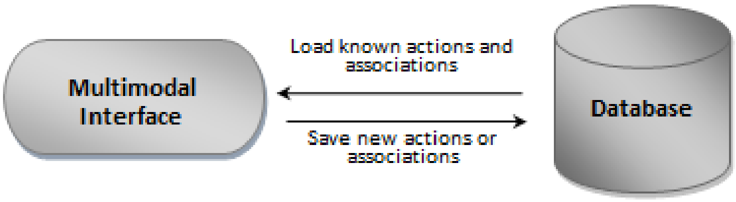


Figure 33: IMI Database.

Graphical User Interface

In order to facilitate the relation between the user and the IMI, typical interface, design principles were followed in its development. The IMI GUI characteristics are related to the design principles that should be followed for multimodal interfaces as described in Section 2.3.1. Therefore, the following characteristics were proposed for the IMI GUI:

- Display the status of each input device (Connected/Disconnected);
- Display the current interface mode (Navigation, Sequence Creator, User Profile);
- Display visual cues for real-time input sequences;
- Show visual cues of the wheelchair trajectory;
- Show visual information of the training sets used for tracing the user profile.

Additionally, to improve the comfort and usability provided by the IMI, another feature is included. It consists of an interactive navigation virtual assistant character, offering advice and information regarding distinct events. This character interacts with the user by giving audio cues, supported by a Text To Speech (TTS) technology. At the same time, the cues should also be presented on the GUI, contained inside a textual area reserved for the purpose. Some of the cues, hints and advices that should be offered by the navigation assistant are: show the current output action being performed; ask for confirmation of an output action request; inform the user whenever an invalid sequence is given; give information regarding control module and input device connection handlers; propose the creation of a new association for output commands without associations; inform the user whenever an attempt to associate an existing input sequence is made and inform the user of the desired inputs for the user profile training session.

4.2.4 Multimodal Interface Architecture

Considering all the proposed features, the overall architecture of the multimodal interface component is presented in Figure 34. This subsection gives an overview of all the system components roles. The components related with the connection of the multimodal interface with the data gathering and data analysis systems will be described in Sections 4.5 and 4.7.

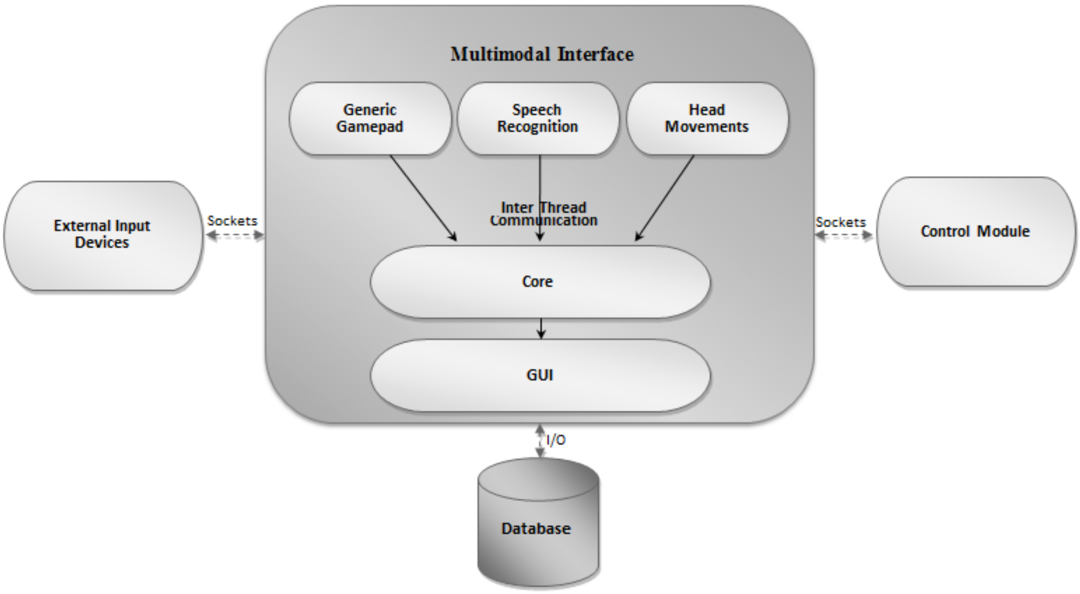


Figure 34: IntellWheels Multimodal Interface Global Architecture.

The IMI is composed by five main components:

- Joystick and Gamepad – Represents the thread responsible for implementing a driver to access a generic gamepad. It handles the device connection and the state of each button: pressed or released. The position of the analog joystick is also read. Its task consists also of implementing an event based mechanism used to notify the core component every time there is a change on the gamepad status.
- Speech Recognition – This component is responsible for accessing the microphone, processing and recognition the voice commands given by the user. It notifies the core component every time a known voice command is recognized.
- Head Movements – This is the component responsible for accessing the device that tracks the users' head movements. One of its functions is detecting specific head

movements and notifying the core component on every detection. Another function is to send, upon request, the users' head relative position to the core component.

- Core – This is the main component of the IMI. One of its functions is to access the database to store and load all the necessary data. It is also responsible for receiving inputs of all the input devices available in the system (internal or external), and implement the algorithms responsible for matching input sequences with desired output commands. Furthermore, it manages the GUI state by sending it information regarding systems events. Finally, it implements the User Profile tracker.
- GUI – The GUI role is to provide a graphical presentation of all the information that might be useful for the user. It also enables the user to control all the available functions on the IntellWheels multimodal interface.

The external components are:

- Control Module – This component interacts with the IMI by initially sending information concerning the commands it can perform. It is responsible for receiving IMI requests and generate the desired system output.
- External Input Devices – This component is composed by a variable number of input devices that might connect to the IMI to extend its multimodality. Each external input device should have a similar behaviour compared to the internal input devices. The only difference is that they are not embedded in the IMI. The communication with these external devices is performed using the protocol described in Section 4.2.5.2 and Figure 37.
- Database – The database task is to store all the information regarding available commands, existing associations and inputs. It also stores the user profiles and the description of the test sets used by the User Profile tracker.

4.2.5 Multimodal Interface Implementation

A prototype of the IntellWheels Multimodal Interface was implemented using the Embarcadero Delphi [292]. This section presents the most relevant implementation details. It includes the description of the basic input modalities that were implemented, the data representation structures that were used and the interaction between all the system's components. Furthermore, the approach used to analyse and validate input sequences is also documented [5] [77].

4.2.5.1 Input Modalities

This section presents the main input modalities that were used: Generic Joystick and Gamepad, Speech Recognition, Head Movements (Figure 35) and a Brain Computer Interface for detecting thoughts and facial expressions. More recently, a Virtual Joystick was also added to the multimodal interface which allows driving the intelligent wheelchair using, for example, a smartphone.

Figure 35: Generic joystick, headset with microphone, wiimote and BCI headset.

A Nintendo Wii Remote was used to implement the component responsible for detecting the head movements. Since the main objective of this experiment was to try to prove the proposed concept, low cost devices that could be easily programmable were used. Next, a more detailed description, concerning the implementation of the IMI embedded input recognition modalities, is presented.

Joystick and Gamepad

Initially a Gamepad was used for the preliminary tests. Since the intended users had difficulties in moving the small joysticks of the gamepad, a USB Joystick with two axis and twelve programmable buttons was used for driving the wheelchair. These types of joysticks and gamepads are widely used in video games once they offer a big number of buttons and analog axis that can be easily programmed to provide an attractive way of navigation. Figure 35 shows an example of the joystick that can be used with the IMI.

Speech Recognition

This feature uses a headset microphone to capture the sound of the users' speech, which is then interpreted by a speech recognition engine. The speech recognition module used in the IMI takes advantage of the Microsoft Speech Recognition Engine. This engine provides an Application Programming Interface, named Speech Application Programming Interface (SAPI) [293]. SAPI allows the use of speech recognition and speech synthesis within Windows applications.

SAPI was chosen since it is a freely redistributable component which can be shipped with any Windows application that wishes to use speech technology. Although many versions of the available speech recognition and speech synthesis engines are also freely redistributable, SAPI offers a standard set of interfaces accessible from a variety of programming languages.

Therefore, it was possible to implement this feature without the need of installing and accessing external software. Besides, it proved to be a very efficient choice since the recognition accuracy was highly satisfactory, even without training for the user's voice before the first use. One interesting feature of the Microsoft Windows SAPI is the possibility of designing grammar rules that can be used for specific contexts. This feature makes it possible to limit the set of recognition hypothesis to a custom set of voice inputs, substantially increasing the recognition accuracy. In order to use this feature for the IMI, a context-free grammar (CFG) was used to store the possible voice inputs [5] [77]. This grammar follows the SAPI grammar format and is stored in a XML document format.

Head Movements

The Wii Remote, sometimes informally named "Wiimote", is the primary controller for Nintendo's Wii console. The main feature of the Wii Remote is its motion sensing capability, which allows the user to interact with a computer via gesture recognition through the use of a three-axis accelerometer [294]. Besides using the Wii Remote accelerometer values to directly control the wheelchair's trajectory, these signals may also be used as inputs to algorithms that detect four distinct head movements: leaning the head forward; the head back; the head right and the head left [5] [77].

The approach consists of defining a threshold value that triggers a small timer. The timer is started if the user leans the head higher than the defined threshold. After the timer event is triggered, the head movement module checks if the head (accelerometer value) is back to the original position. Both the threshold and the interval between the triggered events are configurable and can be adjusted for each user. These head movements can be used to compose input sequences, having a similar function as a voice command or buttons pressed on the gamepad.

Brain Computer Interface

A brain computer interface available for research edition (Emotiv System [295]) was used for controlling the IW with facial expressions and thoughts. The Emotiv kit is composed of several elements of hardware and software.

The Emotiv has different headset possibilities. A headset which only works with approved applications and a developer headset which supports product development and includes a software package. Both headsets are wireless and use a proprietary USB dongle to communicate using the 2.4GHz band. The headsets contain a rechargeable 12 hour lithium battery, 14 EEG saline sensors and an accelerometer.

The acquired Software Development Kit (SDK) was the Research SDK Edition [295]. This edition includes software, such as the Control Panel, the EmoKey, the EmoComposer, the TestBench and the Raw EEG data API.

The Control Panel is an application that can be used to access the EPOC headset information. The Control Panel includes the Expressiv, Affectiv, Cognitiv and a Mouse Emulator, that fulfill the functions of:

- Expressiv set – designed to detect facial expressions based on reading EEG and EMG (electromyography) which is a technique for evaluating and recording the electrical activity produced by skeletal muscles. This component can recognize 12 inputs: blink, right/left wink, look right/left, raise brow, furrow brow, smile, clench, right/left smirk and laugh. An avatar mimics the user's expressions by matching the incoming signals.

- Affectiv set – attempts to monitor the user's emotional states. It can detect engagement/boredom, frustration, meditation, instantaneous excitement and long term excitement.
- The Cognitiv set – monitors and interprets the user's conscious thoughts. It can detect 13 thoughts: push, pull, lift, drop, left, right, rotate left, rotate right, rotate clockwise, rotate counterclockwise, rotate forward, rotate backward, and disappear, as well as the passive neutral state. The software gives feedback in the form of a floating cube that responds to the recognized thoughts. The thoughts can also be associated to commands.
- Mouse emulator – using the accelerometer allows the user to control the mouse by moving their head.

The Emotiv Software detects thoughts using built-in proprietary software. The techniques used by this software to recognize the thoughts and facial expressions are not documented. Only a general description of the methods can be found in the manual [296] and some explanations in the official forum [295]. From this scarce documentation, it is possible to know that some general descriptive features for each channel were developed and some features that capture elements of the descriptions in the literature, such as noise-resistant features to measure the distribution of alpha waves independently on eyes being open or closed were also built. Basically, the procedure was to start by collecting a large number of information, with respiration, skin conductance and heart monitors, along with EPOC prototype headset data and filming the tests of a large number of volunteers to produce a large case database for posterior classification. It was claimed, by the Emotiv, that different thoughts can be mapped to certain actions, for example training the action pull by thinking blue. However, the accuracy of recognition of this kind of task, using the Emotiv software, was very low and, from the experiments it was not conceivable to use the Emotiv recognition system for using the thoughts as inputs.

The EmoKey allows connecting detection results received from the EmoEngine[2] to predefined keystrokes according to logical rules defined by the user. The headset can be used as a control input during application development.

The EmoComposer is an application that emulates the behaviour of the EmoEngine with an attached Emotiv headset. It is intended to be used as a development and testing tool; it

[2] EmoEngine is a logical abstraction that communicates with Emotiv headset, receives preprocessed EEG and accelerometer data, performs post-processing and exposes Emotiv detection results to applications via the Emotiv API [296].

makes it easy to send simulated EmoEngine events and request responses to applications using the Emotiv API.

The TestBench is an application that offers a real-time display of the Emotiv headset data stream. It has several functionalities such as allowing the user to see the EEG contact quality, the actual data coming in from each sensor, the accelerometer data, wireless packet information and battery life. The application displays a Fast Fourier Transform (FFT) of any incoming channel with different possibilities of window size in samples and windowing options and also presents the Delta, Theta, Alpha and Beta bands. Using the TestBench it is possible to record, save and playback data in European Data Format (.edf) and convert saved .edf data to Comma-separated Value format (.csv). Testbench output columns include: Rolling Packet Counter, Interpolation Flag (for occasional lost packets), Timestamp, 14 channels EEG data, multiplexed raw Contact Quality channel, 14 channels interpreted CQ values (0-5 = Black - Green sensors), Gyro X, Gyro Y.

Emotiv Application Programming Interface (API)

The Emotiv Application Programming Interface is a library of functions, for application developers, which enables them to write software applications that work with Emotiv neuroheadsets and the Emotiv detection suites. This API may be used to develop applications in C or C++.

Emotiv and Brain Signals

The brain signals collected with Emotiv BCI (Figure 36) are identical to those collected by medical EEG systems.

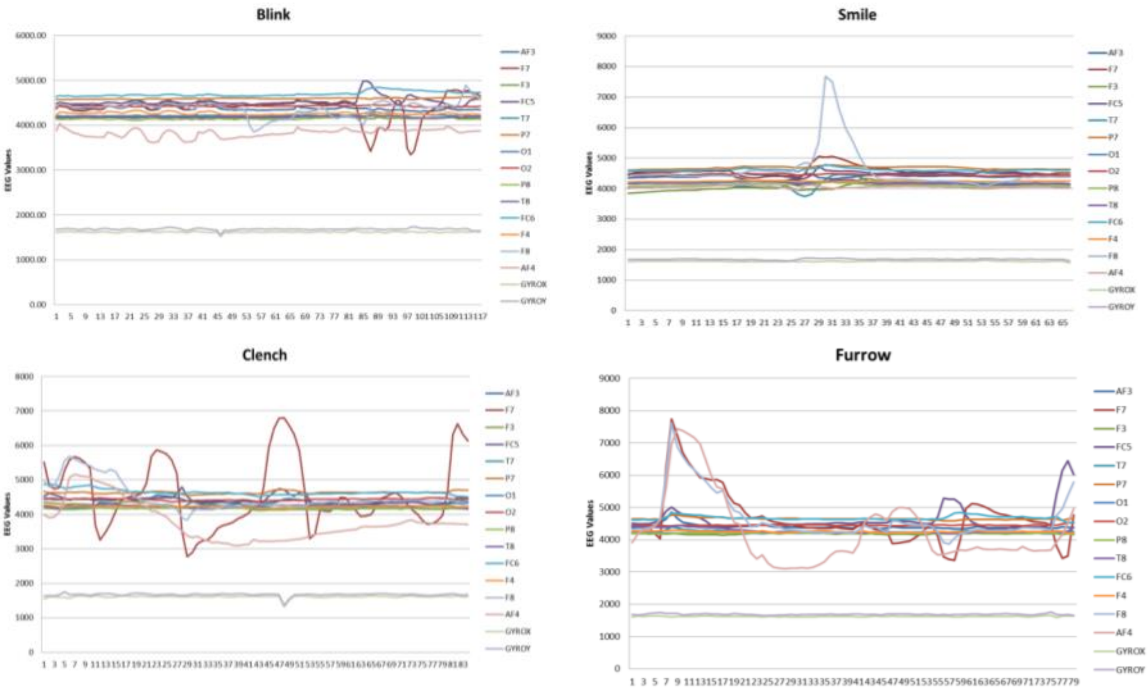


Figure 36: Examples of the values of the EEG channels for different facial expressions.

The referencing system defines the electrical ground point for the measurement of all the other sensors. The measures are the voltage differences between the left-hand reference point and every other sensor. The right-hand reference is a standard feed-forward reference compensation electrode which allows the headset electronics to compensate on top of changes in body potential (for example electrical pickup from lights, power circuits, transformers which change drastically if they are moved to different areas). The left-hand reference is called CMS (Common Mode Sense) and the right-hand reference is called DRL (Driven Right Leg) after the original use in high-resolution ECG systems where it was traditionally attached to the right leg of the patient.

4.2.5.2 External Input Modalities

To accept inputs from external devices, a very simple protocol was implemented (Figure 37). The IMI acts as a server for receiving external sockets connections.

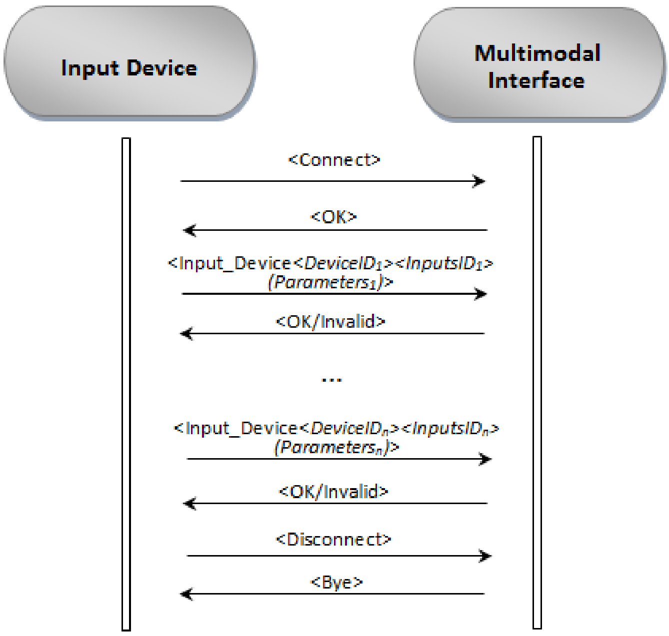


Figure 37: Communication protocol between external input devices and the multimodal interface.

The interaction with an external device has three distinct phases. On the connection phase, the external application should identify itself by sending a command with its name. This information, via navigation assistant, is used to notify the user that a new input device is available. After this phase, the IMI becomes ready to receive inputs from the new input device. On disconnect, the external application should notify the IMI, sending a disconnect command.

4.2.5.3 Commands and Input Sequences Representation

The content of the output commands, input sequences and associations are shown below.

Wheelchair Commands

The output commands provided by the IntellWheels Platform (IWP) control module differ slightly in type and nature and can be divided into four types [5] [77]:

- High-level – the trajectory of the wheelchair's movement is calculated only by the control module of the platform (such as, go forward, go back, turn right, follow right wall) using high-level algorithms to determine the values for the speed of the wheels depending on the action to execute.
- Medium-level – identical to the high level type, whereas the user is responsible for setting the desired speed/angle for the movement, for example defining that a follow right wall will be executed at half speed or a "go to bedroom" command will be executed at full speed.
- Manual-mode – the user is responsible for controlling the wheelchair's trajectory. If the shared control option is activated, the control module of the platform may help by detecting obstacles and avoiding collisions.
- Stop – the wheelchair is stopped and enters a stand-by mode until further request.

To design a generic structure to represent them on the multimodal interface side, the following descriptors were used: the name of the action (name); the action type (type); the kind of parameter to be passed (parameters) and the hint text for the TTS navigation assistant (hint). Typically the high-level commands have no other parameters and are composed by a single action to be executed in an autonomous manner by the IW such as "go to bedroom". The medium level actions may have parameters to configure the wheelchair speed or rotation angle. The manual mode maps the joystick or head position to a given desired linear and angular speed using a giving mapping function/algorithm (see Section 4.4.1.1).

Table 7 shows the relation between each action type and the number of parameters sent, which will generate a certain output.

Action type	Set parameters	Parameter type
High-Level	0	n/a
Mid-Level	1	Speed or Rotation Angle
Manual-Mode	2	Linear Speed and Angular Speed
Stop	0	n/a

Table 7: Action type and parameters.

Depending on the action type, one may need one or two parameters to define the desired output. For sending linear and angular speeds, the value of each axis is directly sent to the mapping algorithm that then transforms it into the motor speed for each of the wheels.

In the mid-level type, the parameter to be passed might be related to the wheelchair's linear speed (e.g. go forward at speed 30%) or to the rotation angle (e.g. spin 90º), depending on the action nature. Other parameters may also be used, such as the action safety, but are not fully implemented on the current version. Since the linear speed requires only one axis, and the rotation angle requires two axis, the parameter descriptor for a mid-level may vary (float or vector). Figure 38 shows an example of how a rotation angle is calculated according to the two axis that are used. In the example, the angle would be calculated using the Wiimote, so the user would lean the head to express the desired rotation angle. For a rotation angle, a vector representation is used.

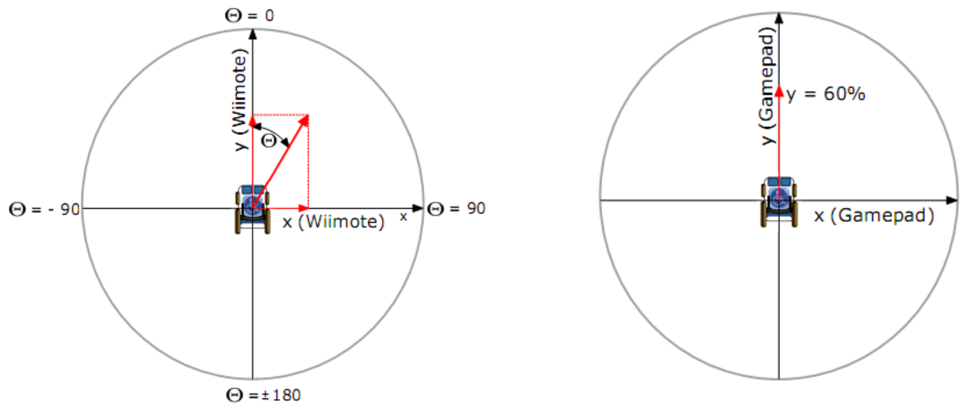


Figure 38: Mid-level rotation angle and linear speed parameters.

To extract a linear speed, a single float number is used, since it is only needed to read the value of one axis. For example, to configure a parameter for an action named "Go Forward at Desired Speed", the user can choose the joystick 'y' axis to express the desired speed. When requesting this action, the user should push the analog switch to a certain position, in order to set the desired speed. In the manual-mode type the vector descriptor is used, since two axis are needed to directly control the wheelchair. Therefore, the linear and angular speeds are sent, since the wheelchair automatically calculates the speed of both wheels according to these parameters [160]. The maximum value for both linear and angular speeds accepted by this wheelchair model is 100. To obtain a correct movement while controlling the wheelchair in manual mode, using the gamepad or the wiimote, it was necessary to normalize the input values to a range varying between 0 and 100.

Input Sequences

An input sequence is composed by one more input tokens. An input sequence is formed by a set of input tokens composed by two parts: device descriptor and input descriptor, assuming the following format: *<device_id1.input_id1 device_id2.input_id2 ... device_idn.input_idn>*. This way, an input sequence must be formed by one or more input tokens. For example the input sequence *<joystick.2 wiimote.right>* means "Pressing the button 2 of the gamepad, followed by leaning the head to the right".

4.2.5.4 Multimodal Interface Commands

Since the IMI offers a different set of features, it was important to think of a way to make them easily accessible by people with physical disabilities. Depending on the level of physical disability, controlling a mouse can be an impossible task for many individuals. For example, to consult the list of available output commands or saved associations, it is necessary to perform two clicks on the interface. Therefore, it was decided to adopt the same style of interaction, not only to request output commands of a certain control module, but also for controlling actions related to the IMI. Using this approach, it was possible to associate an input sequence to a different type of action: interface action. The set of implemented interface actions, embedded in the IMI, can be consulted in Table 8.

Interface command/action	Description
Mouse left	Click left mouse button
Double Mouse left	Double click left mouse button
Mouse right	Click right mouse button
View/Hide Output actions	Open/Close the output actions viewer
View/Hide Associations	Open/Close the list of saved associations
View/Hide Device Manager	Open/Close the input devices’ tabs panel
New sequence	Start the sequence creator mode
Save sequence	Associate sequence to action and save
Calibrate wiimote	Reset the wiimote controller accelerometer values to 0
Enable/Disable Speech	Turn the speech recognition module on or off
Enable/Disable Assistant	Turn the TTS navigation assistant feature on or off
Mouse POV	Enable the control of the mouse using the gamepad´s POV
Mouse wiimote	Enable the control of the mouse using head movements
Minimize/Maximize	Show or hide the applications
Profiler	Start the user profile tracker module

Table 8: List of IMI interface actions (adapted from [5] [77]).

In spite of being a different action type, the structure used to save it is the same as the one used for the output actions, only the *type* field changes.

4.2.5.5 Multimodal Interaction Loop

Control Module versus Multimodal Interface

To allow the interaction between the IMI and the control module, the latter had to be adapted in order to implement the command structure. After the connection process, the control module must send the list of available commands/actions. Additionally, it should also periodically send the availability of each action, namely when there are availability changes. This feature was implemented because some actions depend on external software or hardware, which might go into an unavailable state. Figure 39 and Figure 40 presents the global flow for the control module and the IMI respectively.

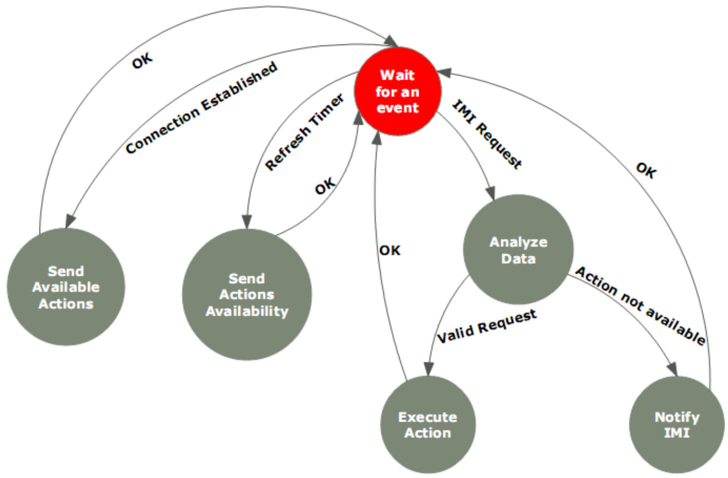


Figure 39: Control module global flow (adapted from [297]).

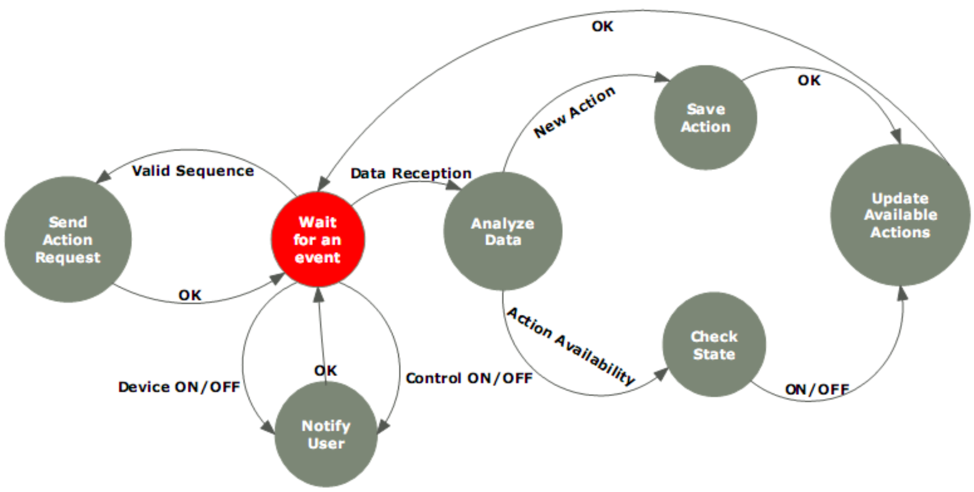


Figure 40: IMI global flow (adapted from [297]).

Sequence Analysis

The input sequence analysis represents the most important feature of the IMI. Each time an input token is perceived by an input device recognizer, a notification is sent to the core component, which is responsible for checking if the current input sequence matches any of the existing associations. The sequence analyser implementation takes advantage of the method used to represent an input sequence. As it was explained before, an input token consists of the pair formed by the device descriptor and the input descriptor.

The approach consists of keeping all the input sequences associated to output actions sorted. In this way, it is possible to apply a binary search every time a new input token is received [5] [77]. The Binary Search algorithm [298] has a good performance and its operation fits this situation, since an input sequence is sequentially growing. Therefore, it is necessary to constantly compare the current input sequence with fragments of the stored associations. If at any time, the user's input sequence does not match any fragment of the same size, the sequence is immediately discarded, and the user is notified. Inversely, if the current input sequence is a fragment of one or more associations, a timer is activated, in order to wait for further inputs that may transform the current input sequence into a valid match. When a match happens, it is necessary to verify if there is any other association composed by the current input sequence and one or more input tokens. In this situation, a different timer is activated. Meanwhile, the IMI waits for further inputs. If no input token has been given by the user when the timer event is triggered, the associated output action is requested to the control module. Otherwise, the timer is turned off and the process takes its normal flow.

Finally, if there is a perfect match, which means that the current input sequence is mapped to an output action, and there is not any other input sequence using the current one as prefix sequence, the associated output action is immediately requested.

Sequence Creator

In order to enable the creation of a new input sequence, and consequent association to an output action, the interface has to switch to a different flow mode. When this process is started, the navigation mode is temporarily halted, by turning off the sequence analysis. In this input sequence creation mode, the input sequence is sequentially updated and kept until the user decides to associate it with a desired output action, or, alternatively, cancels the creation of a new association. At any stage of this process, the user may exit the sequence manager option and return to the navigation mode. Figure 41 shows the IMI flow for the association of a new input sequence to a desired output action.

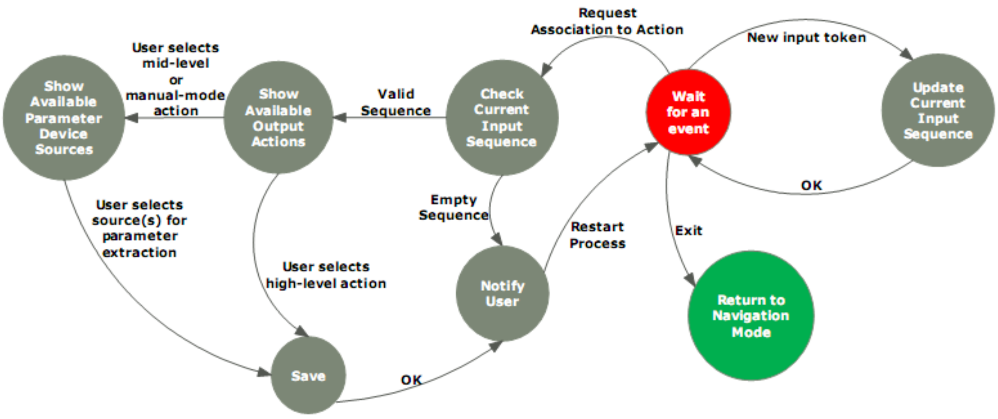


Figure 41: Sequence creator flow (adapted from [297]).

4.2.5.6 Graphical User Interface

A graphical user interface was created in order to present all the necessary information to the user in an attractive, functional and intuitive way. Figure 42 shows the developed graphical user interface for the IMI.

Figure 42: IMI Graphical User Interface.

When the application is launched, the navigation assistant, presented at the top of the GUI, starts by greeting the user. The navigation assistant is responsible for interacting with the user by synthesizing the text presented in the talking balloon that stands on its right side. The text on the balloon changes every time a new event is triggered, in order to keep the user informed of the system's changes. The TTS feature can be switched on or off, either by clicking on the chosen image to represent the navigation assistant, or by associating an input sequence to the interface action responsible for the same setting.

On the top of the interface there is a set of five buttons, which implement the features related with the sequence manager, user profiler and device manager.

To keep the user informed of the availability of the input devices, a set of five icons was placed at the right side of the interface. Every time an input device connects or disconnects from the multimodal interface, its icon changes. Additionally, an icon to represent the control module is also present. In the example presented in Figure 42, the wiimote controller, microphone, BCI and control module were connected to the multimodal interface, however the joystick was not available. Other information provided by the IMI relates to the wheelchair's trajectory. This is done by presenting a set of directional arrows that surround the wheelchair image placed on the left centre of the interface as can be seen in Figure 43.

Finally, the small set of eight icons at the centre of the interface is reserved for the information regarding the input sequences. Every time the user gives a new input token, the respective image for that input token is shown.

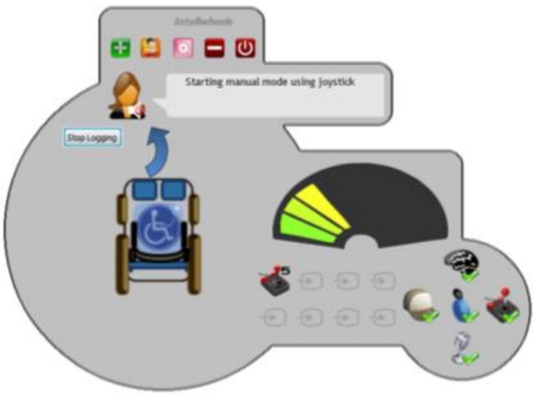


Figure 43: Indication of the direction of the IW in the IMI Graphical User Interface.

Figure 44 shows an example of creation of a sequence using the sequence manager through the IMI. The example presented is a sequence of pressing the button 10 followed by a voice expression, such as “Go”.

Figure 44: IMI graphical user for sequence management.

The IMI also presents the possibility of saving the sequence by clicking in the icon or simple saying “save new sequence”. Other options as cancel or redo are likewise presented in the IMI.

4.3 IntellSim – IntellWheels Simulator

Simulated environments enable easier and more precise data gathering. Besides, they also allow: higher control with lower costs; easy comparison of alternative designs or operating policies; sensitivity analysis; very good training tool; do not have the problem of being susceptible to damage by inappropriate use; easy replication for conducting parallel experiments practical and easy feedback and the possibility of time compression or expansion. Even in the rehabilitation field there are guidelines for using the simulated environment to develop the skills of handicapped people [299].

After the first experiments conducted with the real IW prototype and with the IW simulator it was possible to verify the easiness of acquiring new information in a very fast way using the simulator (opposite to using real prototypes of the IW). However, the achieved results (Section 5.1.1) also showed the importance of environment realism. Therefore, a new 3D and more realistic version of the simulator was developed for the final tests: *IntellSim*.

There are several approaches for creating virtual environments and descriptions of that can be found in Barbosa [300]. Some concentrate attention on graphics, other explore the physical behaviour of objects, fluids or forces and other approaches mix both components.

A simple description of the available methodologies for creating simulated environments is presented in the next sub-sections. It is also presented a more detailed explanation about the USARSim, which is the new platform chosen for creating the scenario for the last tests.

4.3.1 Methodologies for Simulation

The modules for rendering 2D and 3D are known as graphics engines. Usually, they are aggregated inside a game engine, however with specific libraries for rendering. Examples of graphics engines are OpenSceneGraph [301], Object- Oriented Graphics Rendering Engine (OGRE) [302], jMonkey Engine [303] and Crystal Space [304].

The physics engines are software applications with the objective of simulating the physics reality of objects and world. Bullet [305], Havok [306], Open Dynamics Engine (ODE) [307] and PhysX [308] are examples of physics engines. These engines can be used by robotics simulators for a more realistic motion generation of the robot.

Game engines are software frameworks that developers use to create games. The game engines normally include a graphic engine and a physics engine. The collision detection/response, sound, scripting, animation, artificial intelligence, networking, streaming, memory management, localization support and scene graph are also functionalities included in this kind of engine. Examples of game engines are Unreal Engine 3 [309], Blender Game Engine [310], HPL Engine [311] and Irrlicht Engine [312].

A robotics simulator is a platform to develop software for robots modelling and behaviour simulation in a virtual environment. In several cases it is possible to transfer the application developed in the simulation to the real robots without substantial modifications. In the literature there are several commercial examples of robotics simulators: AnyKode Marilou (for mobile robots, humanoids and articulated arms) [313]; Webots (for educational and research purposes; it has a large choice of simulated sensors and actuators available to prepare each robot) [314]; Microsoft Robotics Developer Studio (MRDS) (allows an easy access to simulated sensors and actuators) [315]; Workspace 5 (environment based on Windows that allows the creation, manipulation and modification of images in 3DCad and several ways of communication) [316]. Several non-commercial robotics simulators are also available, as for example: SubSim [317]; SimRobot [318]; Gazebo [319]; Simbad [320]; SimTwo [321] and USARSim [322].

4.3.2 USARSim Description

The USARSim, acronym of Unified System for Automation and Robot Simulation, is a high-fidelity simulation of robots and environments, based on the Unreal Tournament game engine [322]. It was created as a research tool designated as a simulation of Urban Search And Rescue (USAR) robots and environments for the study of human-robot interaction (HRI) and multi-robot coordination [323]. USARSim is the basis for the RoboCup Rescue Virtual Robot competition (RoboCup) and the IEEE Virtual Manufacturing Automation Competition (VMAC) [322].

Nowadays, the simulator uses the Unreal Engine UDK and the NVIDIA's PhysX physics engine. The version used to develop the *IntellSim* was the Unreal Engine 2.5 together with the Karma physics engine (which is integrated into the Unreal Tournament 2004 game (UT2004)). The Unreal Engine maintains and renders the virtual environment while the physics engine models the physical behaviour of its elements. Moreover, it is possible to use its Unreal Editor to quickly develop new objects and environments. Although the migration of *IntellSim* to the new Unreal version is already in development, at the time this work was finished, not all sensor/actuators were already validated and ported.

In its early versions, USARSim included models for differential drive robotic platforms, a restricted set of sensors and the models of three environments. Nowadays, USARSim has models of different sensors, from odometers to encoders and even an omnidirectional camera. Several different robotic platforms can be simulated including wheeled robots, cars, tracked vehicles and flying robots [324].

It is also possible to define the objects behaviour thanks to Unreal Script, which is an ad-hoc script language. USARSim simulates the robots proposed for the Urban Search and Rescue (USAR) routines and the reference test arenas developed by the National Institute of Standard and Technology (NIST) [325].

A useful property of USARSim, which is derived from the original game, is that spectators can observe the scenes by using egocentric (attached to the robot) or third person views of the simulation [323]. The system uses a client/server architecture, as can be observed in Figure 45 [323]. The simulator provides the interactive virtual environment.

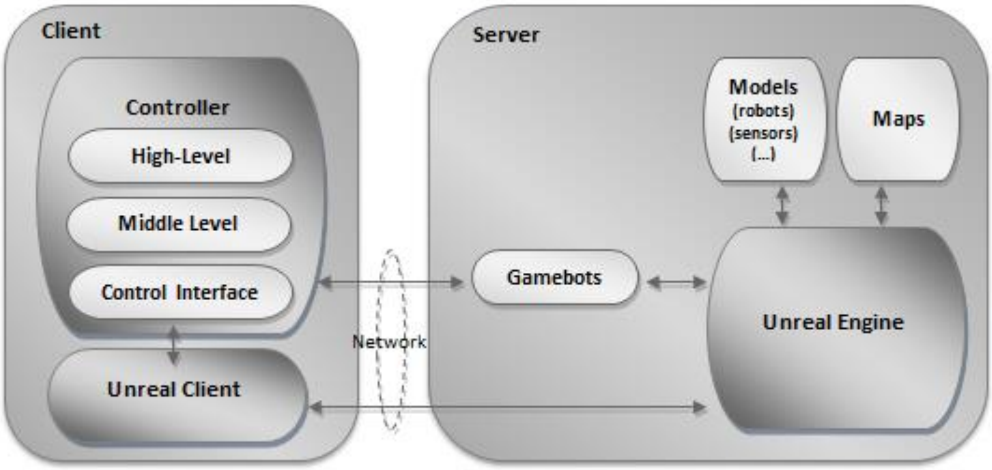


Figure 45: Architecture of the USARSim (adapted from [271] [326]).

The client side includes the Unreal client and the Controller or another user developed application. The Unreal client renders the simulated environment and all the clients exchange data with the server through the network. Typically, the Controller is a user side application namely for robotics, team cooperation and human robot interaction studies. First, it connects with the Unreal server and then it sends command to USARSim to spawn a robot. After the robot is created on the simulator, the Controller listens to the sensor data and sends commands to control the robot. The client/server architecture of Unreal makes it possible to add multiple robots into the simulator [323].

The Unreal server is composed of Unreal engine, Gamebots [327], map and models, such as robot models. The Unreal server preserves the states of objects in the simulator, answers to the commands from the clients by changing the objects' states and sends back data to both Unreal clients and the user side controllers [323]. Gamebots, a modification to Unreal Tournament, was built by researchers to bridge Unreal engine with outside applications [322]. USARSim enables Gamebots to communicate with the controllers using sockets. To support particular control commands and messages, modifications are applied to Gamebots.

4.3.3 USARSim and IntellWheels

As mentioned before, after the first set of experiments it was clear that the realism of the simulated environment and behaviour of the IW should be improved [4]. For that reason, and trying to maintain the principle of developing the IntellWheels' project at the lowest possible cost, the USARSim was chosen as the base for the new simulator. Other reasons to choose the USARSim include its advanced support for robots with wheels, allowing their independent configuration; the capacity to import objects and robots modelled in different platforms in order to facilitate for instance the wheelchair modelling; capacity to program robots and controlling them through the network which enables support for mixed reality experiments [328] [329].

4.3.3.1 Intelligent Wheelchair Model

The virtual intelligent wheelchair (Figure 46) was modelled using the program 3DStudioMax. The visualizing part, which appears on the screen, was imported to the Unreal Editor as separated static meshes (*.usx) files. The model was then added to USARSim by writing appropriate Unreal Script classes and modifying the USARSim configuration file. The physics properties of the model was described in Unreal Script language, using a file for each robot's part.

The model has two free caster wheels and two differential steering wheels. The simulated IW is equipped with the following sensors: camera (Figure 50 shows an image of the first view person obtained by the camera); front sonar ring; laser range finder and encoders. The simulated wheelchair also has a special ground truth sensor that may be used to gather exact (x, y, z) and roll, pitch and yaw values.

Figure 46: Real and Virtual IW.

An important factor affecting the simulation of any model in UT2004 is its mass distribution and associated inertial properties. These were calculated using estimated masses of the different parts of the real chair with batteries (70 kg) and literature values for average human body mass (60 kg). The values obtained for the center of mass and tensor of inertia were used to calculate the required torque for the two simulated motors using the manufacturer's product specification as a guideline.

4.3.3.2 Map and Virtual Environment

A new map was created using the Unreal Editor 3. The map is similar to the place where the patients are used to move around (APPC institution). Several components in the map were modelled using 3DStudioMax [330] and imported into USARSim. Figure 47 presents images of the real and virtual environments.

Figure 47: Real and Virtual Environments.

In order to increase the realism of the virtual environment, several animations using sequence scripts were implemented, such as moving characters.

4.3.3.3 Serious Game in Virtual Environment

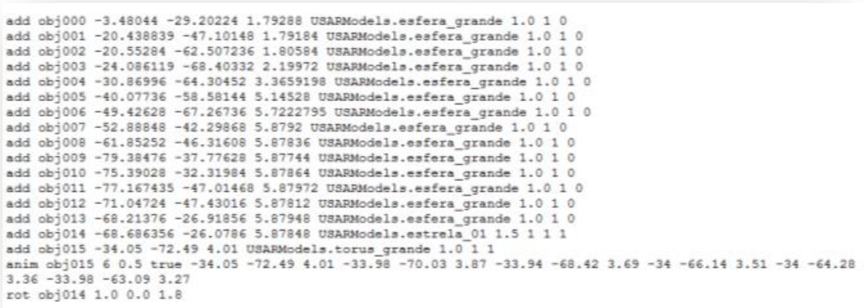
Simulation exercises are interesting solutions [56] to train and evaluate the human abilities, in this case in driving an intelligent wheelchair, and to recognize the needs in term of new functionalities [54]. Using a simulator it is very easy to plan experiments with completely different tasks and including several different levels of difficulty.

The structure and models of the USARSim based IW simulator were presented before. Basically they came to fill the gap between the users and the evaluation of the performance and adaptation of the real wheelchairs. In fact, simulators are platforms that allow a gradual and safe training program and which can help in the transfer of knowledge to the real context [331]. With the training it is possible to learn how to avoid obstacles and how to maneuver in narrow spaces [332]. This transfer of knowledge allows a more frequent use of the wheelchair and for that reason an impact in the quality of life [333]. With this virtual environment it is also possible to monitor at a distance the behaviour of the user giving to them more autonomy and auto-control while keeping safety assured [334].

In this project, and using the virtual environment, a serious game was developed. The objective of this serious game is to give a mental and expertise challenge with specific rules, increasing the motivation for completing the virtual experiment. The users drive the IW trying to attain the serious game objectives, but this allows collecting information about the users' performance in several different tasks.

The game, developed using *IntellSim*, enables to define circuits in a given scenario and place objects (balls and stars) that mark the intended path and should be collected by the user. The user drives the wheelchair collecting the objects, that disappear after being collected. The system gathers performance data concerning the collected objects, collisions and the time taken to complete the task.

A new Unreal client was developed in order to enable flexible and extensible addiction of objects into maps. Figure 48 shows an image of the application and a snapshot of a file storing a game configuration.



```
add obj000 -3.48044 -29.20224 1.79288 USARModels.esfera_grande 1.0 1 0
add obj001 -20.438839 -47.10148 1.79184 USARModels.esfera_grande 1.0 1 0
add obj002 -20.55284 -62.507236 1.80584 USARModels.esfera_grande 1.0 1 0
add obj003 -24.086119 -68.40332 2.19972 USARModels.esfera_grande 1.0 1 0
add obj004 -30.86996 -64.30452 3.3659198 USARModels.esfera_grande 1.0 1 0
add obj005 -40.07736 -58.58144 5.14528 USARModels.esfera_grande 1.0 1 0
add obj006 -49.42628 -67.26736 5.7222795 USARModels.esfera_grande 1.0 1 0
add obj007 -52.88848 -42.29868 5.8792 USARModels.esfera_grande 1.0 1 0
add obj008 -61.85252 -46.31608 5.87836 USARModels.esfera_grande 1.0 1 0
add obj009 -79.38476 -37.77628 5.87744 USARModels.esfera_grande 1.0 1 0
add obj010 -75.39028 -32.31984 5.87864 USARModels.esfera_grande 1.0 1 0
add obj011 -77.167435 -47.01468 5.87972 USARModels.esfera_grande 1.0 1 0
add obj012 -71.04724 -47.43016 5.87812 USARModels.esfera_grande 1.0 1 0
add obj013 -68.21376 -26.91856 5.87948 USARModels.esfera_grande 1.0 1 0
add obj014 -68.686356 -26.0786 5.87848 USARModels.estrela_01 1.5 1 1 1
add obj015 -34.05 -72.49 4.01 USARModels.torus_grande 1.0 1 1
anim obj015 6 0.5 true -34.05 -72.49 4.01 -33.98 -70.03 3.87 -33.94 -68.42 3.69 -34 -66.14 3.51 -34 -64.28
3.36 -33.98 -63.09 3.27
rot obj014 1.0 0.0 1.8
```

Figure 48: Game application and configuration file.

During the game the users are aware of their score, basically the number of collected objects. Several different sounds and animations were assigned into the objects for defining different actions. Objects can be added, deleted, saved and loaded.

The application game (IntellWheels Game) communicates with the simulator (Figure 49) and has access to the information about the position of the wheelchair.

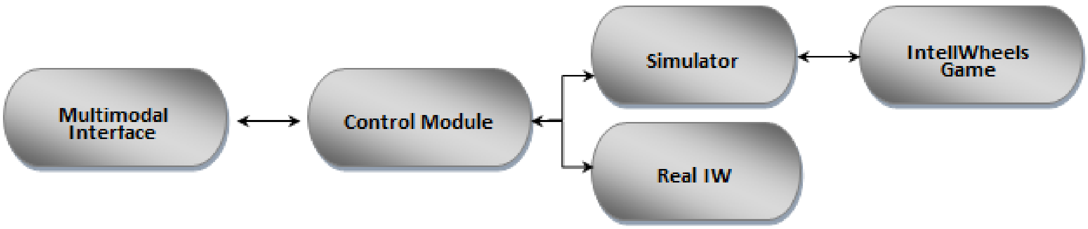


Figure 49: IntellWheels Game interaction.

The objects to collect (serious game targets) have their collision component turned off (in the USARSim simulation properties) and, consequently, the IW can pass through them. Knowing the position of the IW and the position of the objects, the IntellWheels game removes the objects when the IW is near the object. This removal operation adds a point to the game score. The radius distance at which objects are removed and the sound associated to the removing operation can be configured. The position of the wheelchair is also available in the display of the serious game console application together with information concerning its sensors and the global state of the game.

As mentioned before, a set of simple rules was defined for playing the game. During the game the user should drive the intelligent wheelchair, using the multimodal interface, and following a route with the direction marked in the floor with green arrows. The objective is to collect all the blue balls (objects) and a star which defines the end of the route. All the obstacles should be avoided and users should spend the lowest possible time although no time limit was imposed. Figure 50 shows a sequence of images from the game where the objects that should be collected can be observed.

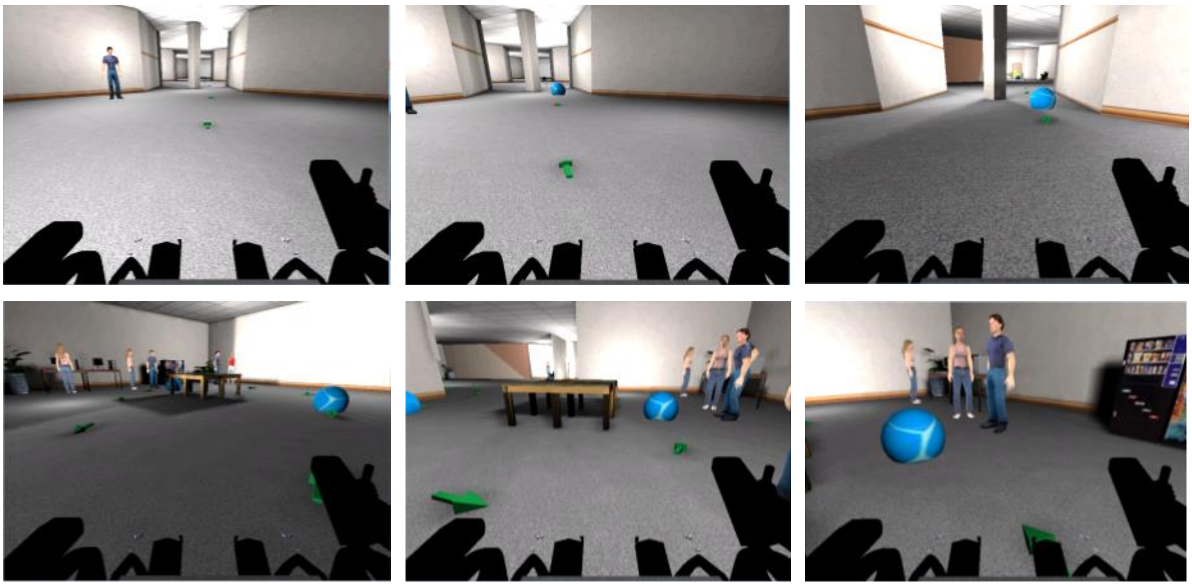


Figure 50: Snapshots of the first person view during the game.

The overall circuit starts with an easier part and then more complicated navigation tasks are introduced, for example the user should descend a ramp, pass through a room with low illumination and through a room crowed with dynamic objects and narrow spaces. Although the developed games were quite simple, the designed serious game architecture and scenarios enable to define much more elaborated games.

4.4 Wheelchair Control

One initial objective of the IntellWheels project was to be able to control the wheelchair using three distinct methods: manual, shared and automatic (Section 2.4.4). During the project several manual and shared algorithms have been developed, but their comparative evaluation had never been performed. In the course of this work several experiments were designed and conducted to provide the best manual, shared or automatic control adapted for the patients.

4.4.1.1 Manual Control

The mapping of joystick positions to individual IW wheel speeds can be performed in an infinite number of combinations and it determines the manual control behaviour. For that reason, several of these mappings were tested with real users in a simulated environment. From the users' feedback interesting conclusions about mappings were achieved [11] [335]. The achieved results show that a linear mapping, with appropriate parameters, between the joystick's coordinates and the wheelchair wheel speeds is preferred by the majority of the users.

Consider that the joystick handle position is represented in a Cartesian coordinate system, with two axis, x and y, which vary between -1 and 1. These (x, y) coordinates can be used to determine the distance of the handle to the central (resting) position of the joystick (0, 0) and an angle relating to a reference vector (which is usually (0, 1)). The desired speed of the left wheel (L) or the right wheel (R) is represented by normalized values (between -1 and 1). With positive values the wheels rotate forward and with negative values the wheels rotate backward.

All mappings should meet the following conditions, that were defined based on an intuitive judgement of what should be the manual control behaviour: θ is measured in respect to vector (0, 1) in the direction of the *yy* axis; when θ is undefined assuming (x, y) = (0, 0), both wheels will be stopped; when $\theta = 0$, both wheels move forward at the same speed; when $\theta = \pm\pi$, both wheels move backward at the same speed and when $\theta = \pm\pi/2$, the wheels rotate in opposite directions at the same speed.

Original Mapping

The first mapping algorithm is very simple. The steering and power mapping is achieved through the use of both x and y in all instances and the wheelchair can rotate around itself when the joystick is pushed to the sides. Assuming that x and y are normalized and vary between -1 and 1 the system of equations that describes the mapping can be observed in Equation 32:

$$\begin{cases} R = y - x \\ L = y + x \end{cases} \quad \textbf{(Eq 32)}$$

Note that at the central position (0, 0) no power is sent to the wheels. When *x* is near 0, and the joystick is pushed forward/backward, the speed increases proportionally to *y*, and the wheelchair moves forward/backward. There is no rotation because *x* equals zero, thus left speed and right speed are equal.

For all other values of *x*, when the joystick is pushed to either left or right, the right speed is proportional to (*y*-*x*) and left speed is proportional to (*y*+*x*). It is important to notice that the right speed and left speed are clipped when (*y*-*x*) or (*y*+*x*) are above the maximum (or below the minimum) normalized values. This implies a loss of the useable joystick area. Additionally, some filtering was added, so that minimal (*x*, *y*) variation near both axis is ignored. When the wheels rotate in opposite directions, speed is halved on both wheels in order to turn the narrow curves more controllable.

With this algorithm steering the wheelchair requires accurate precision. The wheel speed variations that result from lateral joystick movements are quite steep, and when moving forward, little variations on the joystick horizontal axis result in a big adjustment of the direction.

A derived mapping can be obtained when the input variables are squared in order to attenuate the steep changes in wheelchair direction. A significant improvement in terms of range extension was verified with this modification [11] [335].

Proportional Mapping

In the proportional mapping the distance of the handle to the centre of the joystick (ρ) is proportional the maximum wheel speed and the angle (θ) of the joystick relating to the vector (0, 1), that is the *yy* axis, determines how the speed is distributed to the wheels. In order to keep ρ in the 0 to 1 range, the value is clipped when ρ is above one. Assuming that *x* and *y* are normalized and vary between -1 and 1, the control follows these conditions:

$$R = \begin{cases} \rho, if\ 0 \le \theta \le \frac{\pi}{2} \\ \rho.\frac{-\theta + 3.\pi/4}{\pi/4}, if\ \frac{\pi}{2} \le \theta \le \pi \\ -\rho, if\ -\pi < \theta < -\frac{\pi}{2} \\ \rho.\frac{\theta + \pi/4}{\pi/4}, if\ -\frac{\pi}{2} \le \theta \le 0 \end{cases} \quad \textbf{(Eq 33)}$$

$$L = \begin{cases} \rho.\frac{-\theta + \pi/4}{\pi/4}, if\ 0 \le \theta \le \frac{\pi}{2} \\ -\rho, if\ \frac{\pi}{2} \le \theta \le \pi \\ \rho.\frac{\theta + 3.\pi/4}{\pi/4}, if\ -\pi < \theta < -\frac{\pi}{2} \\ \rho, if\ -\frac{\pi}{2} \le \theta \le 0 \end{cases} \quad \textbf{(Eq 34)}$$

where $\rho = \sqrt{x^2 + y^2}$ and $\theta = \mathrm{atan2}(-x, y)$.

If ρ > 1, ρ is clipped to 1 and if ρ < -1, ρ is clipped to -1.

When compared to the previous algorithm this provides a more pleasant driving experience, however steering is still not as smooth as desired. The joystick axis values were also attenuated with a quadratic function creating a new mapping that was tested in the real user experiments.

Intuitive Mapping

This mapping alternative is an updated version of the original mapping. Assuming that *x* and *y* are normalized and vary between -1 and 1, the equations are:

$$\begin{cases} R = y - nx \\ L = y + nx \end{cases} \quad \textbf{(Eq 35)}$$

the value *nx* follows the Equation 36:

$$nx = \begin{cases} u_1 c_{\text{point}} + (x - c_{\text{point}}) \times u_2 \quad if \quad x > c_{\text{point}} \\ -u_1 c_{\text{point}} + (x + c_{\text{point}}) \times u_2 \quad if \quad x < -c_{\text{point}} \\ u_1 x \quad if \quad -c_{\text{point}} \le x \le c_{\text{point}} \end{cases} \quad \textbf{(Eq 36)}$$

where $c_{\text{point}} \in [0,1]$; $u_1 \in [0,1]$ and $u_2 \in [0,1]$. The tested values were $c_{\text{point}} = 0.2$; $u_1 = 0.5$ and $u_2 = 0.25$.The first slope u_1 allows a fast curve and the next slope u_2 after the cut point (c_{point}) should allow a slower curve.

4.4.1.2 Automatic Control

The developed automatic control has as its main objective enabling the IW to follow a predefined circuit without the need of user's intervention. The automatic control assumes full control over the navigation of the wheelchair and executes the navigating task following the circuit points without any user intervention. A predefined circuit can be specified by defining the relevant circuit points and the wheelchair can autonomously drive to the specified points. The users in the study performed predetermined tasks such as collecting objects along the circuit.

The main reason to create an automatic control was concerned with the methodology used to achieve a shared driving algorithm for the intelligent wheelchair. This automatic control assumes the self-localization problem solved and hence the IW always knows its position in the environment. Before this work, the IntellWheels IW was already capable of some forms of automatic control that did not rely on localization, such as "follow wall" or other high level actions like "go forward" [336]. However, it still missed an automatic driving algorithm based on the current position and orientation and the desired position and orientation.

Figure 51 shows the main idea of the implemented algorithm. If the IW would move directly from target to target, it would have to stop and turn on the spot at each target. This is a very unnatural way of driving the IW. In order to have a smoother path, the IW should consider not only the next target, but also the target that follows. Following this principle, the position of the wheelchair in the world referential (*x*, *y*) is combined along with the position of the target (*T*) and the next target (*NT*) in order to determine a corrected target (*CT*) of the trajectory.

$$CT = T + d_{[CT,T]} \times \frac{\overrightarrow{NT\,T}}{\left\| \overrightarrow{NT\,T} \right\|} \tag{Eq 37}$$

With the introduction of the corrected target it is possible to have a smoother trajectory of the wheelchair.

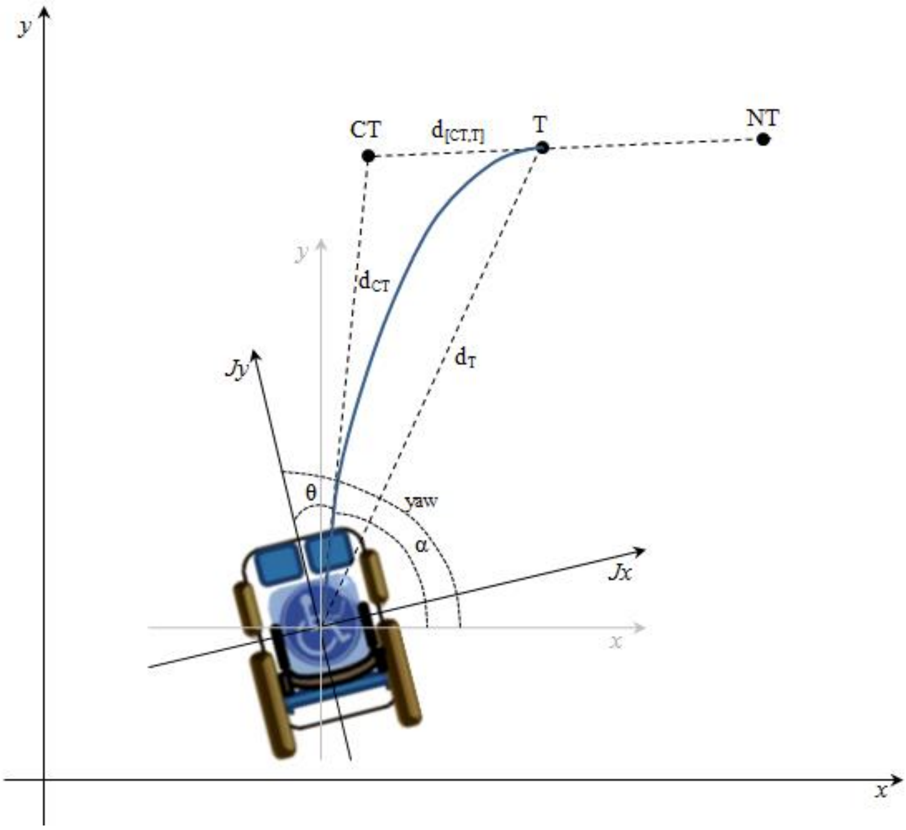


Figure 51: Automatic action of following circuit.

The corrected target is calculated using a ramp function for the $d_{[CT,T]}$ as shown in Figure 52 and has the same direction as the target (*T*) to the next target (*NT*).

$$d_{[CT,T]} = \begin{cases} 0 \quad if \quad 0 < d_T < a \\ \dfrac{d_{\max}}{b-a}\,\mathrm{d_T} - \dfrac{a \times d_{\max}}{b-a} \quad if \quad a \le d_T < b \\ d_{\max} \quad if \quad b \le d_T < +\infty \end{cases} \tag{Eq 38}$$

A maximum distance $d_{[CT,T]}$ (d_{max}) could be chosen, considering for example the surrounding obstacles, in the Figure 52 it has a value of 0.5 units and a has the value 0.5 and b has the value 1.5.

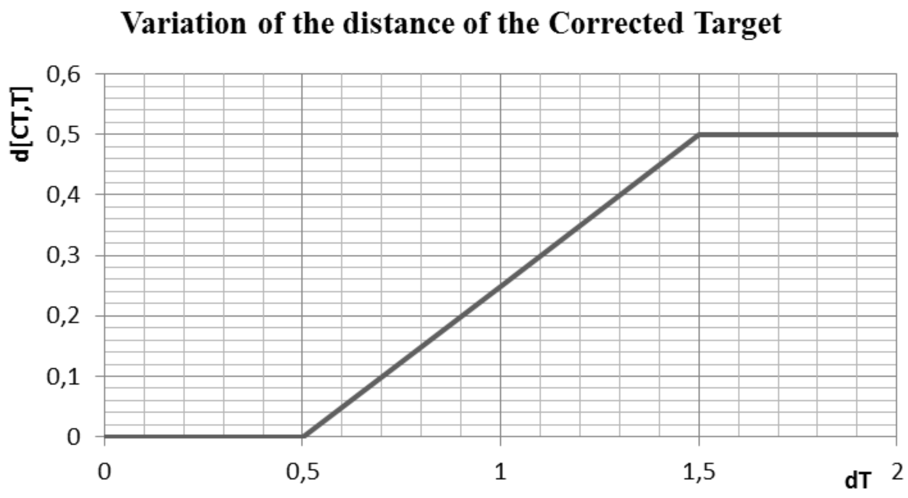


Figure 52: Variation of the distance of the corrected target.

The distance of the target to the corrected target is determined by the value of the ramp function using the distance of the wheelchair to the target (d_T) as input. Knowing this distance, the position of the corrected target may be determined by projecting the point along the next target to target line at this distance from the target. Using this information and the difference between yaw and angle α it is possible to calculate the direction of the joystick relatively to the corrected point (θ).

4.4.1.3 Shared Control

The concept behind the implemented shared control is to understand the intention of the user while providing an easier and safer navigation. This means that, for example, if a user has a high level of difficulty in driving the IW but his intentions can be recognized, the shared control helps the navigation of the wheelchair. Additionally the wheelchair takes control when the navigation of the patient endangers its own safety, in situations such as potential collisions with objects. The computer momentarily takes control and acts on the wheelchair, taking into account the information from sensors and the commands from the user. A more concrete example is given in Figure 53.

The principle is to filter the position of the joystick provided by the user considering the aid level to be introduced and the proximity of the joystick position with the position given by the automatic control. If the position of the joystick is at a higher distance than a given threshold from the automatic control command then it uses the user command otherwise it uses a weighted average of the automatic control and manual control. The weights used in the weighted average determine the aid level that is provided to the user.

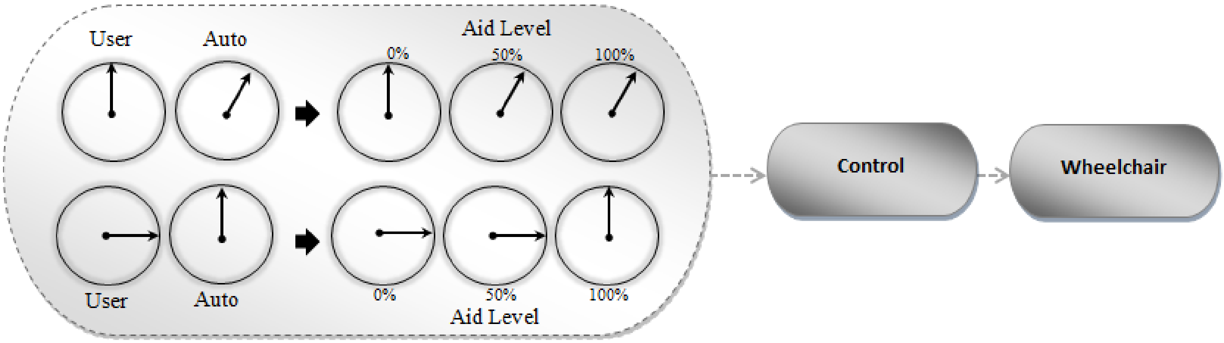


Figure 53: Aided control with respect to the user and to the automatic control.

The implementation of the shared control also considered the obstacle avoidance procedure with the information of the sensors present in the IW. With this tool a more confident way of driving the IW is executed by the users with severe disabilities.

4.4.1.4 Control Selection

The experience using the simulator allows testing the ability of users to drive the wheelchair with several input devices and with a command language. After that, and also using information from user profiling, it is possible to verify if an extra help should be provided to the user. Users can be provided with manual control, shared control with the aided level or even completely automatic control (Figure 54). This automatic control could be used, for example, by the patient's escort such as a relative or medical personal in order to avoid them from the need to manually push the wheelchair to the intended target.

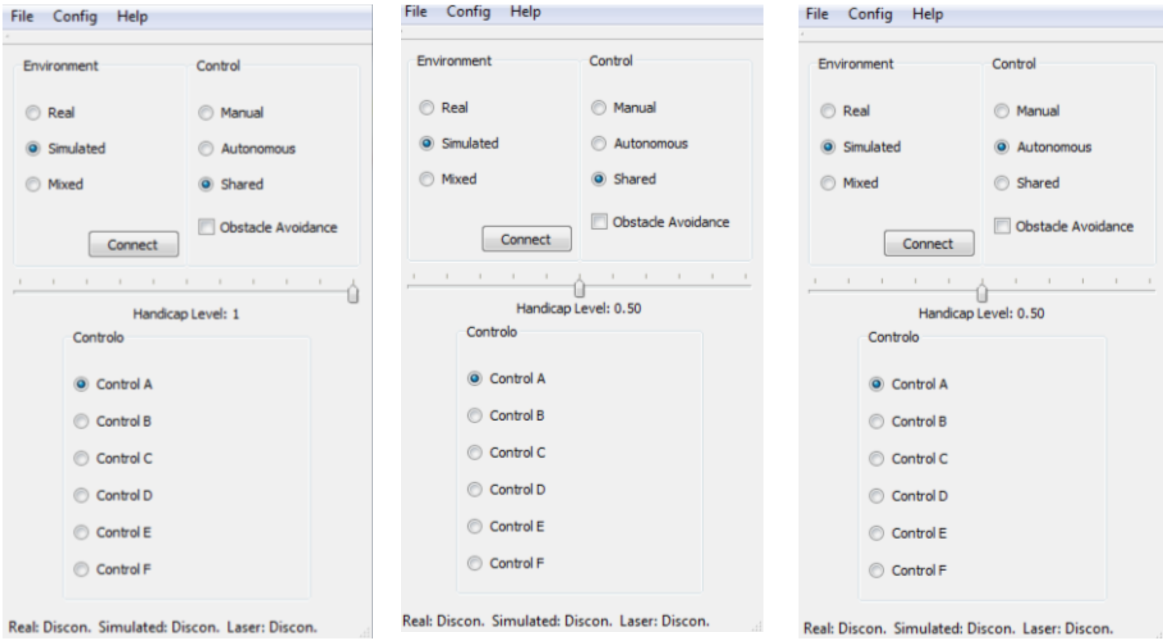


Figure 54: Control selection window.

The tasks and circuits can be defined with an increasing degree of difficulty. It is possible to model real situations such as dynamic and crowded environments; different light conditions; uneven floor and narrow spaces. The information about fatigue, frustration and performance such as number of complete tasks accomplished and number of collisions are indicators of the use of a more adaptable control. Using the Control selection window, the user or a specialist, can specify the control method that best suits each user or situation.

4.5 Multimodal Data Gathering and User Profiling

In order to be able to extract patient models and also environment models, a complete multimodal data gathering system was implemented. Figure 55 presents a global view of the research approach concerning the data gathering and data analysis systems. Based on the IntellWheels prototype and using the real and simulated environments, the work was focussed on planning appropriate data gathering and data analysis systems that enable the creation of an adapted interface and command language adjusted to the patient and where information about the environment is also considered.

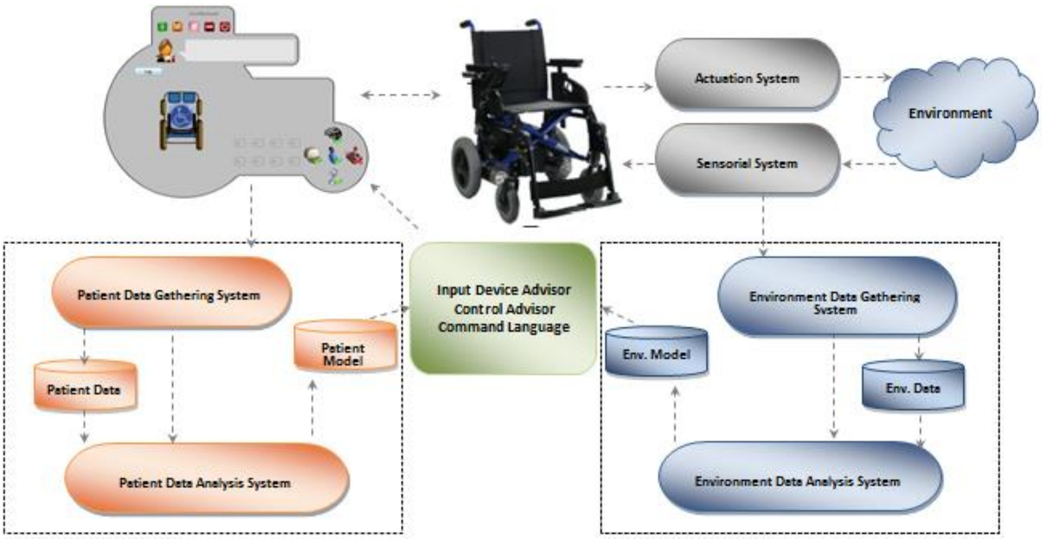


Figure 55: Data gathering and data analysis systems.

The multimodal data gathering system enables the collection of real-time input information from patients with distinct disabilities. The system also enables the collection of environmental information and more high-level information concerning the wheelchair localization and orientation and task in execution, among other information. Figure 56 presents an informal representation of the proposed architecture for the multimodal data gathering system concerning patient data gathering.

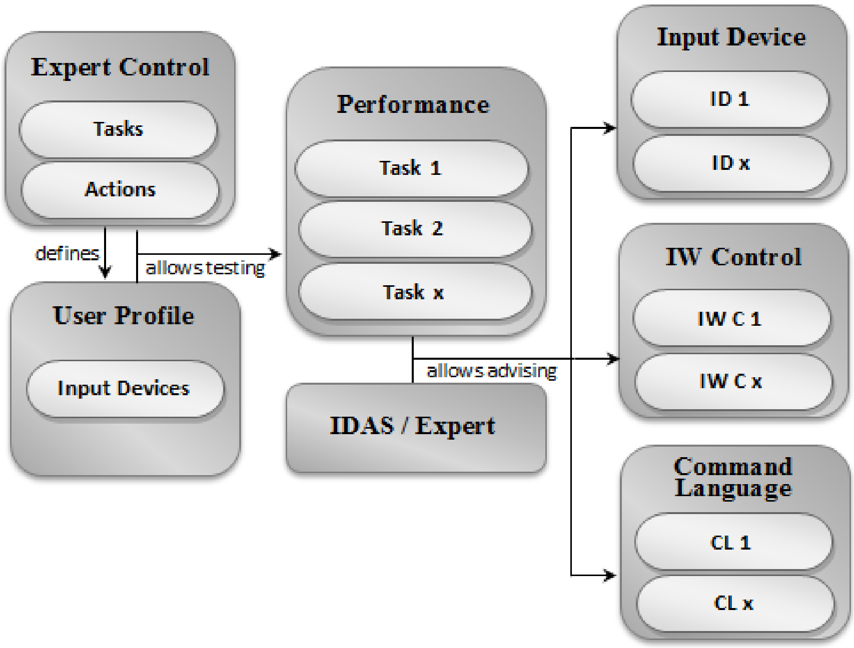


Figure 56: Multimodal patient data gathering system.

A user profiling module was designed and implemented. This module, along with the IntellWheels Data Analysis System, helps in the process of giving the more adequate input device for driving the wheelchair. Initially a set of tasks and actions was defined to be executed by the user. A wizard, or more specifically the profiling component of the multimodal interface, includes simple tasks that can be performed with input devices and that permit an evaluation of the user ability to use that device. The performance of each task was collected and the specialists (occupational therapists) were integrated in the process to confirm the correct classification. The data analysis system advises the user about the best suited input(s) device(s) and command language. The system also records the information about each user and if the user wants to update the information.

The IW environment information was also subject of study (Figure 57). A global positioning and sensing system was used to collect data concerning the global wheelchair movement in the environment. This system also enabled the collection of information concerning both the wheelchair tasks under execution and the environmental conditions, such as crowded level.

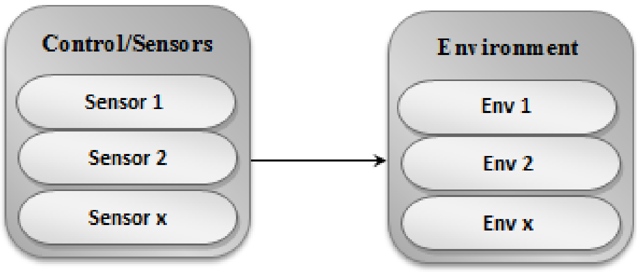


Figure 57: Environment data gathering system.

Considering the concept of flexibility and IntellWheels multimodality, the required data to collect may origin from many sources: input devices, sensors (both real and virtual) and the simulator.

Figure 58 presents the system architecture from where the data can be acquired [337]. The Control application can connect to both the real IW and the Simulator, gathering and processing data from their defined sensors.

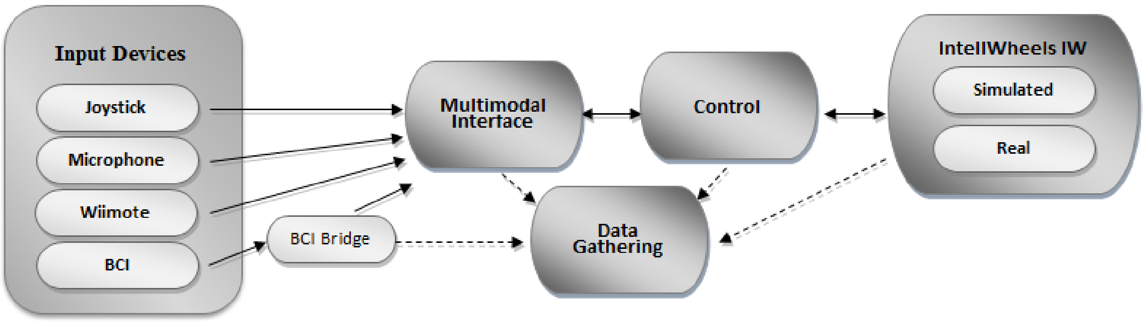


Figure 58: Connections between the applications from where the data can be acquired.

The Control acts as a server regarding data communication with the Multimodal Interface, which in turn, acts as the server of input devices connections.

The data acquisition system is distributed among the Control application, the Multimodal Interface, the input devices bridge applications, simulator and eventually data from the real wheelchair. Therefore, one file with captured data is created by each application as presented in Figure 59.

In order to synchronize the files, a timestamp is attached to all acquired information. As different applications may run in different computers a protocol was established to allow a global synchronization of the timestamps. A flow to set the same virtual uptime for all applications was created: the Control application, the first one to be executed, sends its uptime to the Multimodal Interface, which in turn sends this value to all input devices' bridge applications. Each application has a delta time variable which stores the difference between its own uptime and the Control's uptime. The virtual uptime equals the own uptime added to the delta time. The delta time variable is updated several times throughout the acquisition process, as after a certain amount of inputs received by the Multimodal Interface, the Control application resends a message with its current uptime, which is redistributed to all applications by the flow previously explained.

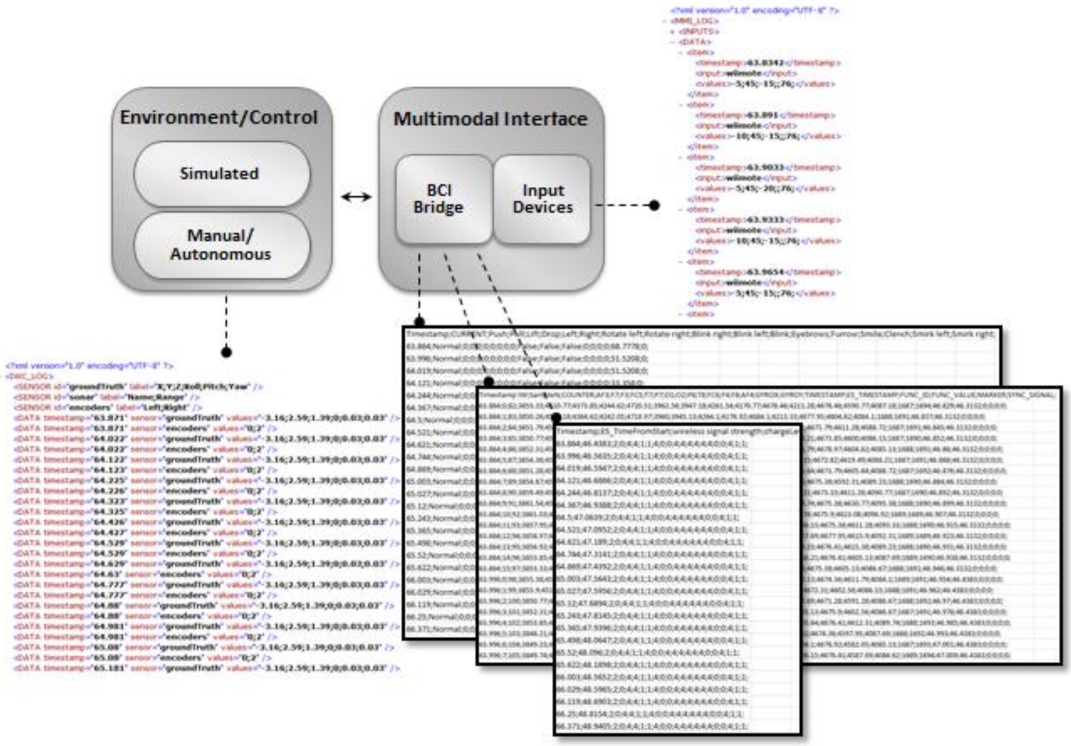


Figure 59: Data from the control, multimodal interface and input devices bridge.

To save the data, the extensible markup language (XML) was chosen due its flexibility. A header element is created in each file containing the description of each type of data the application gathers.

4.5.1 Input Devices Data

One of the most important aspects of the IntellWheels project is how the user interacts with the IW. Gathering information from the several devices is required, and since the IntellWheels interface is multimodal and several input devices can be used to drive the wheelchair, the commands interpreted by the IntellWheels are also important for later analysis. As the Multimodal Interface module controls all inputs from the user and also interprets them, this part of the experiment data can be collected from it.

- **USB Joystick -** The most basic input device that the IntellWheels wheelchair offers is a generic joystick, which allows to control the IW by using its buttons (automatic mode) or by using the analog stick (manual mode and shared mode). When using this device in automatic mode, the data that can be collected are the activated buttons and when they are activated. While in manual or shared mode, the coordinates of both analog sticks must be acquired.

- **Microphone -** The voice recognition module allows registering the voice command given and its recognition confidence. Additionally, it is also possible to collect the noise level and interferences that affect the voice recognition module.
- **Wiimote -** Regarding the head movement input device, the data to capture is composed by the three axes accelerometers values and the buttons pressed. Additionally, the battery level is registered along with the coordinates (x, y) interpreted by the three axes accelerometers values.
- **Brain-Computer Interface -** The data received by the Emotiv headset includes 14 EEG channels and the values of the accelerometer. Figure 60 shows the 10-20 International System the EEG channels that are included in Emotiv headset (sign in green).

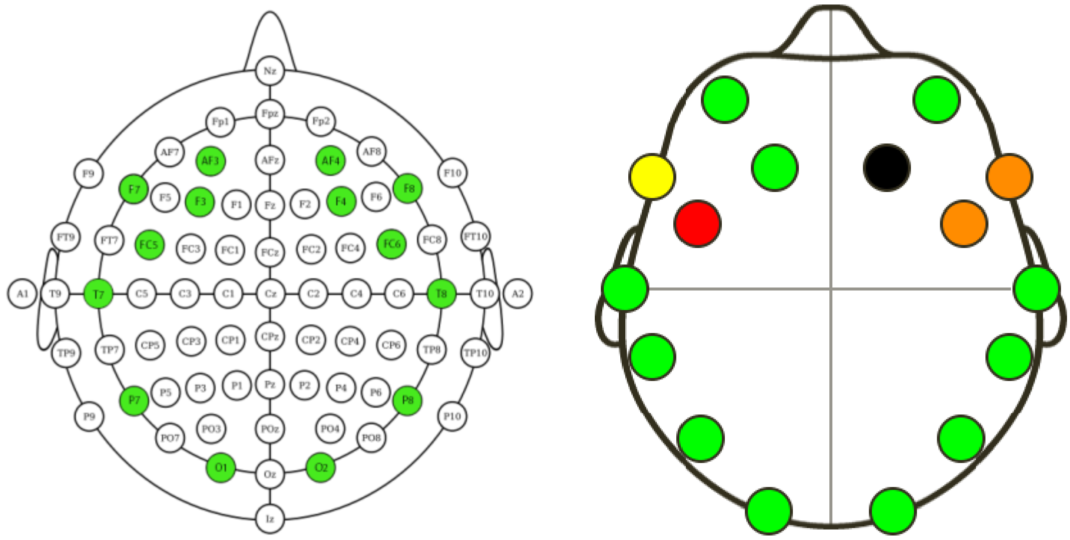


Figure 60: EEG channels included in Emotiv headset.

The data that can be acquired is explained in next list, where the labels highlight the meaning of the variables:

- COUNTER is a rolling counter for the data packet, from 0-127. The sampling rate is 128Hz.
- INTERPOLATED is a flag showing whether the driver had to interpolate the EEG and accelerometer values due to a corrupt or missing data packet.
- AF3; F7; F3; FC5; T7; P7; O1; O2; P8; T8; FC6; F4; F8; AF4 are the raw data from each sensor where the EEG signal units are microvolts.
- RAW_CQ value shows a multiplexed impedance measurement for each channel (it is a relative measurement of conductance). The letters CQ stand for Contact Quality.
- CQ_AF3; CQ_F7; CQ_F3; CQ_FC5; CQ_T7; CQ_P7; CQ_O1; CQ_O2; CQ_P8; CQ_T8; CQ_FC6; CQ_F4; CQ_F8; CQ_AF4; CQ_CMS; CQ_DRL are the threshold of the Contact Quality indicators. The contact quality ranges from green (best

contact possible), yellow (fair contact), orange (poor quality), red (very bad contact) to black (no signal received). The right side of Figure 60 presents the position of the BCI's sensors and a graphic representation of the sensors quality. The CQ_CMS and CQ_DRL are the contact quality indicators of the left-hand reference and the right-hand reference, respectively.

- GYROX and GYROY are horizontal and vertical accelerations from the accelerometer.

When using the BCI to recognize facial expressions only the identified expression is acquired by the Multimodal Interface application along with the system uptime. In order to connect the Brain-Computer Interface (BCI) to the Multimodal Interface application, an additional application is necessary and in this bridge application it is possible to collect data from the variables, such as: percentage of recognition of the correctly identified facial expressions; contact quality about each of its fourteen sensor pads as well as raw EEG data for each channel; the wireless signal strength between the device and its USB receiver and the charge level of its battery.

The bridge application connects to the Multimodal Interface as a client and sends the recognised facial expressions to be used as inputs in the Multimodal Interface. This allows associating a high-level order to an expression or sequence of expressions on the Multimodal Interface.

Currently, from the possible BCI inputs, only the facial expressions are used to control the IW. The Emotiv BCI used in IntellWheels also detects user specific cognitive data and emotional states in real-time, however the accuracy on the thoughts detection is rather low and thus thoughts are not currently used as one of the main inputs of the multimodal interface. In the initial experiments performed with 10 volunteers it was not possible for any of the volunteers, during two hours of training, to deliver a well-defined cognitive thought that could be useful for driving the IW using the methods available for thought recognition on the Emotiv BCI. Thus it was decided not to use thoughts in the final experiments.

Although it was not possible to achieve an accuracy that enabled to use thoughts for driving the IW using standard Emotiv BCI recognition methods, an attempt was made to define better recognition methods by analyzing the available data using data mining methodologies associated to Hjorth Parameters.

4.5.2 Sensors and Simulator Data

The Control application is the bridge between the sensors and the IW, in all of its available operating modes (“Real”, “Simulated” and “Mixed”), so all the sensor data can be collected from it.

The Control application runs in cycles of 100 milliseconds, hence the capturing resolution is also 100 milliseconds. The sensors used in the simulated wheelchair are the same as those used in the real IW. The Control module connects the IW to the simulator; therefore collecting information from the simulator is similar to acquiring data from the sensors. The variables that can be acquired from the simulator through the Control are related to the Ground Truth such as the localization in space (x, y, z), the roll, pitch and yaw of the IW; the name and range of the sonars; the (x, y) and range of the laser range finder and the values of the encoders.

As in the real prototype 16 sonars and a laser range finder were place in two side bars. Two encoders were also included, and coupled to the wheels to allow odometry. These sensors provide the wheelchair's ability to avoid obstacles, follow walls, map the environment and see the holes and unevenness in the ground.

Figure 61 represents the location of the sonar sensors present in the intelligent wheelchair which are marked in blue and the laser range finder marked in green.

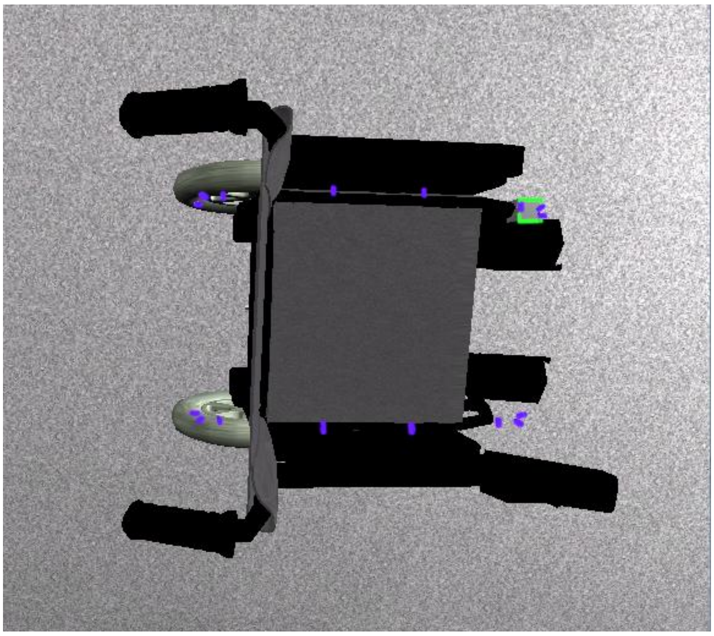


Figure 61: Representation of sensors localization.

In the next images (Figure 62) it is possible to confirm the localization of the sensors in the simulated and real wheelchair.

Using the simulator it was also possible to model rooms with low illumination and noisy environments and test the performance of users while driving the wheelchair.

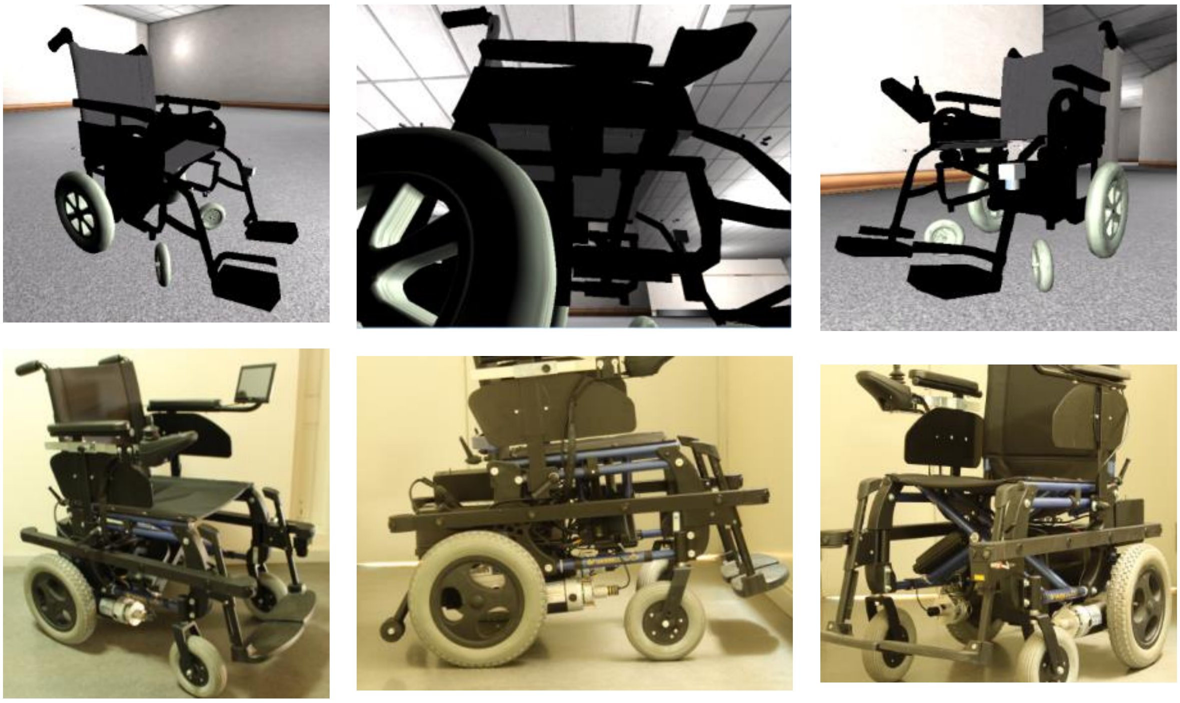


Figure 62: Virtual and real intelligent wheelchair.

4.5.3 User Acquisition Data

The data gathering process also involved individuals which were essential to test all the modules in the different phases. The individuals were selected among the students at Escola Superior de Tecnologia da Saúde do Porto/Instituto Politécnico do Porto (ESTSP/IPP) and from individuals with distinct disabilities such as cerebral palsy with distinct degrees of severity, with dystonia, spastic tetraparesis, diplegia and patients suffering from myopathies from Associação do Porto de Paralisia Cerebral (APPC). The Ethics Committee of the APPC was consulted and the informed consent (Annex B) was also provided and signed by all the participants.

The data collecting process was divided into two parts. In each of the parts, the individuals were asked to:

- Perform obligatory inputs, including a complete set of a previously specified protocol: voice commands; facial expressions; head, arm and hand movements.
- Perform free inputs, the individuals were asked to perform some given tasks and using its own and completely free preferred interaction modalities.

The tests were performed using the simulator and with distinct environmental conditions: noise and lighting variations; distinct pavement; dynamic environment and parallel tasks such as maintaining a conversation while driving the IW.

The data from the individuals were also collected using questionnaires. With these questionnaires it was possible to select the sample for the tests, to evaluate the preferences regarding each control method for each task in each environmental condition and to obtain results for applying the supervised learning methodologies for the data analysis system.

4.5.3.1 User Data

The questionnaires about the user incorporate validated scales to classify the cerebral palsy degree and to measure the usability of the intelligent wheelchair. More details on the questionnaires are presented in the rest of this section.

The Gross Motor Function Classification System (GMFCS) [338] [339] is a standard instrument used for cerebral palsy classification. The GMFCS measures the changes in the global motor function. GMFCS is accepted by the majority of the professionals and considered to be easy to apply [339]. The classification provided by the GMFCS divides the cerebral palsy individuals into five levels:

- Level I – walks without limitations;
- Level II – walks with limitations;
- Level III – walks using a hand-held mobility device, for example canes, crutches, and anterior and posterior walkers;
- Level IV – capable of self-mobility with limitations and can use a powered mobility device; meaning that actively controls a joystick or an electrical switch that enables independent mobility. The mobility base may be a wheelchair, scooter or other type of powered mobility device;
- Level V – this is the highest level where the individual is mainly transported in a manual wheelchair. Physical impairments restrict voluntary movement control and the ability to maintain antigravity head and trunk postures.

In this study the GMFCS was used to select the sample, since the individuals with cerebral palsy should be potential users of the intelligent wheelchair (levels IV and V).

A questionnaire for pre-selection of the modalities (Annex C) was developed. This questionnaire was filled by occupational therapists that have the patients to their care. The objective of this questionnaire was to pre-select the input devices that should be tested, reducing the time consumed on each test section and the user frustration of being completely incapable of driving the wheelchair with that specific input device. Individuals the therapists considered as incapable of using any of the input devices were excluded from the study.

After the experiments using the simulator, a questionnaire (Annex D) was applied to the individuals that could answer the questions. This questionnaire was divided into four parts:

- User identification: Several questions about the gender, weight, height, level of education, presence of motor, cognitive, visual, audio and sensorial constraints and experience using ICT (Information and Communication Technologies);

- Usability and Safety: Questions related with usability (integration of the System Usability Scale [340]), safety and control;
- Controls of the IW: Questions regarding the level of satisfaction with the different existing input modalities of the IW, such as joystick in manual and high level mode, voice commands and head movements, as well as the integration of all kind of modalities;
- Fatigue and Frustration: Questions related with the level of fatigue, frustration and degree of difficulty and preferences using the different inputs.

This questionnaire provided information about the users' opinions of the experiments, the usability of the intelligent wheelchair and the multimodal interface. In fact, although a user could have a higher performance, in terms of test time or collisions, and with a specific input device that does not mean that it is the preferable choice for that user.

The preference study of the manual and shared controls integrated a different validated scale. In this case, the Computer System Usability Questionnaire (CSUQ) [341] was used. The users should also rank the different control modes by their preference and indicate how easy it was to drive the IW in narrow spaces using different control modes (Annex E).

4.5.3.2 User Profiling

This section presents the User Profile methodology. This methodology intends to evaluate the user capability to voluntary control different inputs by performing simple interactive tests that do not involve the IW. The diagnostic derived from these tests can be very useful to adjust certain interface settings allowing an optimized configuration and hence improved interaction between the user and the multimodal interface.

The IntellWheels Multimodal Interface was enriched with a module (Figure 63) capable of performing series of training sessions, composed of small tests for each input modality. These tests may consist, for example, of asking the user to press a certain sequence of buttons on the gamepad, or to move the joystick to a certain position. Another test may consist in asking the user to pronounce a set of voice commands, or to perform a specific head movement.

The tests can be performed sequentially and can have different difficulty levels. Additionally, the tests are reconfigurable and extensible through a profile specification language based on XML. Finally, the test sets and their results can be saved on a XML database, accessible by the IntellWheels Multimodal Interface. The quantitative measures consist of: the time taken to perform a full button sequence; the average time between pressing two buttons; the average time to place the joystick on a certain position; the average time to position the head on a certain position; the trust level of speech recognition; maximum amplitude achieved with the joystick or gamepad analogical switches in different directions; maximum amplitude achieved with the head in different directions and number of errors. Using the quantitative measures, the following qualitative measures can be estimated: user ability to use joystick and the gamepad buttons; user ability to perform head movements and user ability to pronounce voice commands.

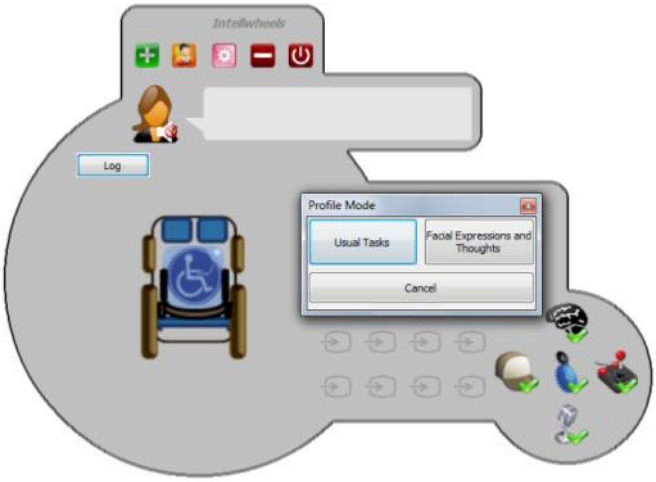


Figure 63: Starting user´s profile module.

At the end of the training session, the tracked user information is saved to an external database, containing the users' profile. The user profile can be used to improve security, by defining, for each user, a global trust level for each input modality. The trust level can be used to advise the user on the modalities to use, at the creation of a new association. Confirmation events can be triggered whenever an input with a low trust level is detected.

Definition of the Test Sets

To perform the profile tests described in the previous section, a simple XML grammar was defined (Figure 64). It implements four configurable distinct test types: sequences of buttons; voice commands; positions for both joysticks (when using the gamepad) and head positions.

```
<INTELLWHEELS_PROFILER>
  <BINARY_JOYSTICK>
    <item>
      <sequence>joystick.1  joystick.2
      </sequence>
      <difficulty>easy</difficulty>
    </item>
  </BINARY_JOYSTICK>
<ANALOG_JOYSTICK>
(…)

<ANALOG_WIIMOTE>
  <item>
    <x>100</x>
    <y>0</y>
  </item>
</ANALOG_WIIMOTE>
  <SPEECH>
    <item>go forward</item>
    <item>turn right</item>
    <item>create new sequence</item>
    <item>stop</item>
  </SPEECH>
</INTELLWHEELS_PROFILER>
```

Figure 64: Example of XML containing user profile test set.

The proposed XML grammar makes it possible for an external operator to configure a test set that it may find appropriate for a specific context or user. When a user starts the training session, the different types of tests are iterated. In order to attain a consistent classification of the user, the defined tests should be sufficiently extensive. The test set present on the XML file is iteratively shown to the user. It starts by asking the user to perform the button sequence as can be observed in Figure 65.

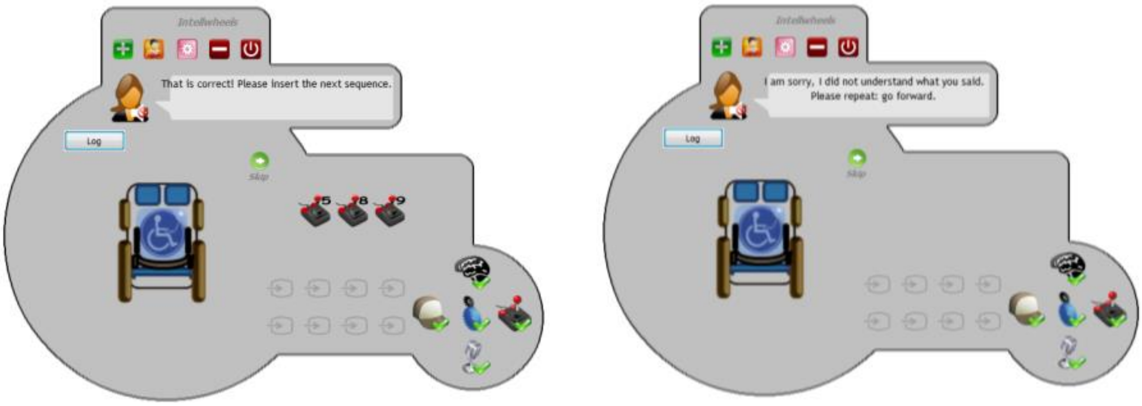


Figure 65: User profiler gamepad and voice tests.

When the user ends the first component of the user profiler module, the navigation assistant asks the user to pronounce the voice commands stored in the XML and if it does not recognize the message, asks the user to repeat the voice command (a limited number of times) (Figure 65).

The last part of the user profiler test is shown in Figure 66. The user is invited to place the joystick into certain positions. A similar approach is used for the head movements test.

Figure 66: User profiler joystick test.

To define the user proficiency in using the gamepad buttons, a very simple method was implemented. Each sequence defined on the grammar should have an associated difficulty level (easy, medium or hard). The difficulty type of a sequence may be related to its size, and to the physical distance between the buttons on the gamepad. Since the layout of a generic gamepad may change depending on the model, defining whether or not a sequence is of easy, medium or difficulty level is left to the operator.

BCI: Facial Expressions and Thoughts

The user profile on BCI inputs is not integrated in the Multimodal Interface Application and a specific application was developed for this task. The application presents animations and images of facial expressions and thoughts that the user should mimic as can be observed in Figure 67, and collects information from the BCI on the cerebral response of performing these facial expressions and thoughts.

Figure 67: Facial expressions and thoughts mimic application.

The possible options for the facial expressions are: smile; left smirk; right smirk; blink the eyes; blink the left eye; blink the right eye; furrow; clench; eyebrows and normal. The possible thoughts are: forward; back; left; right; left spin and right spin.

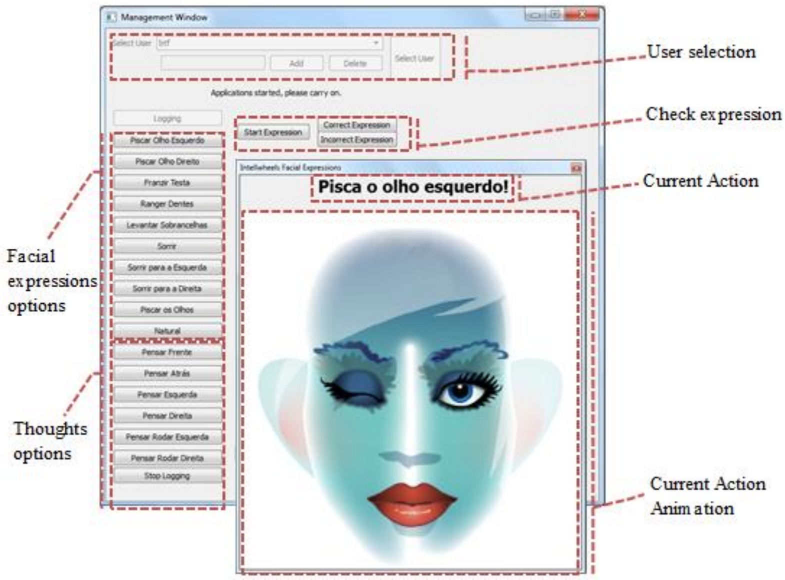


Figure 68: Management window and window with facial expressions.

In order to manage the tests and to provide expert data on the moments of execution of facial expressions another application was developed: the management window. With this application it is possible to remotely command which test the user performs. In particular, for the facial expressions data acquisition, extra information was added. The occupational therapist, for example, could register the start and finish of the facial expression execution or thought test and also register if the facial expression was correct or incorrect. Figure 68 presents the management window and the window that could be remotely in another monitor with the animation of the facial expressions and thoughts.

As referred in Section 4.5.1 using the raw data from the 14 sensors and accelerometer values of the Emotiv BCI it was also developed a system capable of pre-processing the raw data and then applying data mining algorithms in order to perform facial expression and thoughts classification. Several steps were performed in this phase of pre-processing. Figure 69 shows a general overview of these steps.

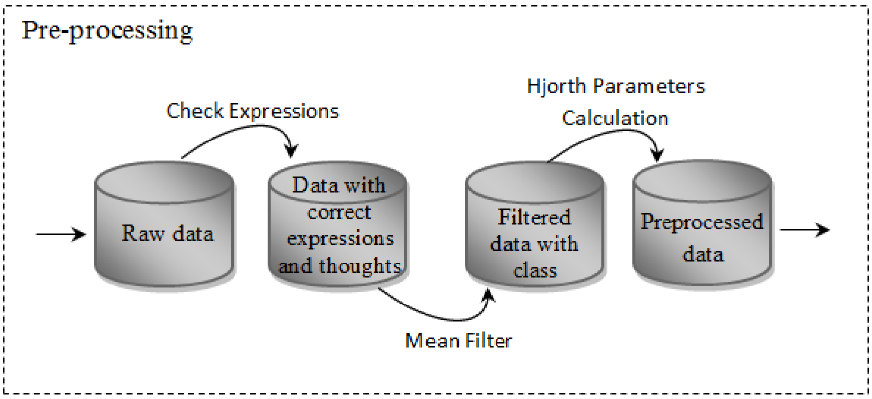


Figure 69: Overview of the pre-processing stages.

After checking if the expressions were performed correctly, it was applied a mean filter to the partial sampling of the EEG sensors (14 sensors) as in Equation 39 and the two accelerometer series of values as in Equation 40:

$$\bar{x}_{EEG^j} = \frac{1}{k}\sum_{i=1}^{k} EEG_i^j \quad \textbf{(Eq 39)}$$

$$\bar{x}_{Gyr^j} = \frac{1}{k}\sum_{i=1}^{k} Gyr_i^j \quad \textbf{(Eq 40)}$$

where $k = 0, \ldots, n_{partial\ sampling}$ and j is the timestamp that correspond to a facial expression or thought.

Next, in order to extract the features, the Hjorth parameters for each expression and thought were calculated [7] [9]. The Hjorth parameters present three measures to characterize the EEG signals in terms of amplitude, time scale and complexity. These parameters can discriminate between mental states. The parameters were obtained using the following Equations:

- Activity (Ac) – it is a measure of the mean power of the signal. It is measured using the standard deviation of the signal:

$$S_{Ac}^{i} = \frac{1}{l}\sum_{i=1}^{l}(S^{i} - \bar{S}^{i}) \qquad \textbf{(Eq 41)}$$

where l is the amplitude of time corresponding to the facial expression or thought; i=1,…16 and S is the filtered signal.

- Mobility (Mo) – it represents the mean frequency in the signal. This measure can be calculated as the ratio of the standard deviation of the slope (S_{d}^{i}) and the standard deviation of the signal as in Equation 42:

$$S_{Mo}^{i} = \frac{S_{d}^{i}}{S_{Ac}^{i}} \qquad \textbf{(Eq 42)}$$

- Complexity (Co) – the objective with this measure is to capture the deviation from the sine wave (the softest possible curve). It is expressed as the number of the standard slopes actually seen in the signal during the average time required for one standard amplitude deviation. Equation 43 allows calculating the complexity:

$$S_{Co}^{i} = \frac{S_{dd}^{i}}{S_{Ac}^{i}} \qquad \textbf{(Eq 43)}$$

where S_{dd}^{i} is the standard deviation of the second derivative of the EEG signal.

At this stage the dataset was composed of the Hjorth Parameters for all EEG and accelerometer values as features and the class composed of all valid expressions and thoughts [7] [9].

After the first experiments an optimized selection of variables was applied to eliminate irrelevant and redundant features. Forward selection was applied which is characterized for starting with an empty selection of attributes and, in each round, it adds every unused attribute of the given set of examples. For each added attribute, the performance is estimated. Only the attribute giving the highest increase of performance is added to the selection. Then a new round is started with the modified selection. Finally, several data mining techniques were tested with 10-fold cross-validation for the best performance. The algorithms applied for comparison were: Naïve Bayes; Support Vector Machines, Neural Networks, Nearest Neighbour and Linear Discriminant Analysis.

4.6 Manager Application

Using the manager window the therapist can select the profile tests and every option about the simulation environment. The maps, the initialization of the intelligent wheelchair and the options about the serious game can be configured in the manager window (Figure 70).

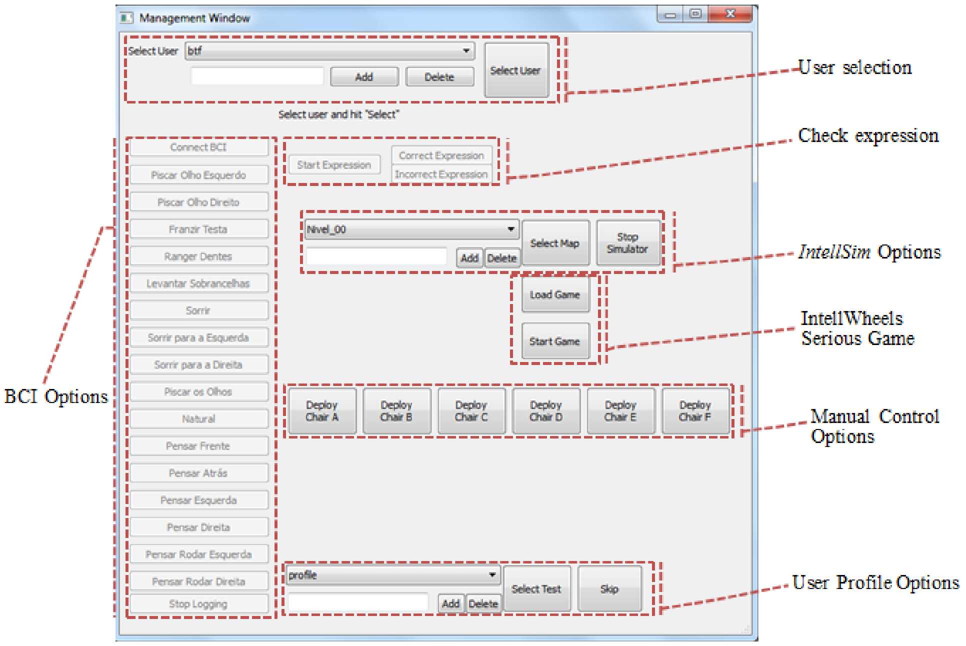


Figure 70: Management window application.

The first part of the manager application is concerned with the user selection enabling to add new users that are going to make the tests, delete users and select existing users for using the system. User profiles are incremental and thus, selecting a given existing user results in improving the user already existing profile.

After selecting a given user, the manager application simplifies the process of launching the complete system by automatically launching the multimodal interface and control module. Also, after selecting the simulator and game characteristics, the manager application launches the IW simulator and the IW serious game applications and connects all the applications with the data gathering system in order to be able to perform the test and record the results.

The manager also enables the therapist to select the simulator options, including the map to be used and the level (circuit to be performed) on that map. It also enables to load a given game inserting the objects on the circuit to be performed and selecting the game options such as the way to measure the user performance.

The control mode may also be controlled by the therapist using this control window. For that, options to select one of the available manual controls (six in Figure 70) are included, together with options to select the level of user handicap in order to use an appropriate shared control mode (see Section 4.4.1.4 for details).

The user profile options may also be selected in this window including defining the set of tests to be performed by the user for profiling and the BCI expressions to be performed for user BCI profiling.

This manager window was crucial to the execution of a large set of tests with real patients giving full control to the therapist over the profiling and testing process.

4.7 Data Analysis System

The IntellWheels Data Analysis System (IDAS) is the component that advises the user on the best input device for driving the intelligent wheelchair and kind of control that should be used to help in the wheelchair driving process. Moreover, the IDAS, using information from the pre-processing module of multimodal data fusion, is capable of extracting the most relevant information from the patient data gathering system application (profile module) which enables fast generation and configuration of the interfaces. This configuration enables the creation of a command language adapted to the user. Besides advising the best kind of input device(s), the system may also advise the best options for driving the intelligent wheelchair including the best set of input sequences and its association with the available commands. For that reason, the best choice for the command language is going to consider the best recognition combination, the best efficiency and the best intuitiveness combination. The objective is to have the best association of inputs and commands, considering the user characteristics, to drive the intelligent wheelchair.

This means that it is necessary to first define a set of commands. For example using five commands, as in Table 9, associated to an input sequence set:

Inputs sequences	Commands
Press button 1	"Go Forward"
Press button 1 – Press button 2	"Go Back"
Press button 1 – Tilt the head to the right side	"Turning Right "
Say “Go” – Say “Left”	"Turning Left "
Smile	"Stop"

Table 9: Input sequences associated with commands.

In the next section the IDAS requirements, in order to provide the best interface for a specific user, are going to be presented.

4.7.1 Requirements

The IntellWheels Data Analysis System has several requirements that should be fulfilled:

- Enable multiple input devices – the command language should be able to include inputs from different input devices so that it has a higher range of facilities for driving the IW;
- Maximize user performance in driving the IW – the objective is to present a solution where the performance, usability and safety is maximized;
- Be adapted to multiple users with distinct disabilities – the IW should be available and adapted to different users and to different disabilities;
- Fast response to user commands – the time between starting an input sequence and executing the corresponding command should be minimized;
- Associate several distinct input sequences with similar performance to the same command – the fulfilment of this option allows a user which degrades for example one of his abilities, to be able to drive the IW with another set of options;
- Intuitiveness between the associations of the input sequences and the commands – the user should use input sequences that are user friendly, for example saying "Forward" should mean that the wheelchair should go forward or "Blink the right eye" should mean that the wheelchair should turn right instead of going left.

In order to explain the proposed solutions the definition and formalizations of confusion matrix for each input device are presented in the next subsection.

4.7.2 Inputs' Confusion Matrix and Measures

The data acquisition system in the Profile Module also provides the information about what was asked and what was recognized by the system. For that reason it is possible to obtain a confusion matrix for each input and for each input device.

Definition 9: The **confusion matrix of each input device** can be designated as in Equation 44:

$$CM_{ID} = (n_{ij})_{\substack{i=1,\dots,N \\ j=1,\dots,N}} \qquad \textbf{(Eq 44)}$$

where i designates the lines, j the columns of the matrix, n_{ij} is the number of times that I_j is recognized as I_i and ID is the input device.

Example 9: Assuming that there are three input devices (Brain Computer Interface; Microphone and Joystick) and that each input device allows performing several inputs (I_i). The matrices CM_{BCI}, $CM_{Microphone}$ and $CM_{Joystick}$ are illustrated in the next three tables, where also simple examples are given for each of the inputs.

Table 10 represents the confusion matrix with several inputs that can be executed by a user and recognized by the brain computer interface. The inputs here presented are blink, smile, clench, furrow and eyebrows.

CM_{BCI} — Predicted \ True	I_1 (Blink)	I_2 (Smile)	I_3 (Clench)	I_4 (Furrow)	I_5 (Eyebrows)
I_1 (Blink)	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}
I_2 (Smile)	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}
I_3 (Clench)	n_{31}	n_{32}	n_{33}	n_{34}	n_{35}
I_4 (Furrow)	n_{41}	n_{42}	n_{43}	n_{44}	n_{45}
I_5 (Eyebrows)	n_{51}	n_{52}	n_{53}	n_{54}	n_{55}

Table 10: Confusion matrix defined for the brain computer interface.

Table 11 represents the confusion matrix with the inputs that can be expressed saying "Go"; "Left", "Right", "Back" and "Stop".

$CM_{Microphone}$ — Predicted \ True	I_1 ("Go")	I_2 ("Left")	I_3 ("Right")	I_4 ("Back")	I_5 ("Stop")
I_1 ("Go")	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}
I_2 ("Left")	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}
I_3 ("Right")	n_{31}	n_{32}	n_{33}	n_{34}	n_{35}
I_4 ("Back")	n_{41}	n_{42}	n_{43}	n_{44}	n_{45}
I_5 ("Stop")	n_{51}	n_{52}	n_{53}	n_{54}	n_{55}

Table 11: Confusion matrix defined for the microphone.

Table 12 presents the results for the confusion matrix when the inputs are the directions of the movements produce with the joystick. The arrows symbol the directions of the joystick.

$CM_{Joystick}$ — Predicted \ True	I_1 (↑)	I_2 (←)	I_3 (→)	I_4 (↓)	I_5 (/)
I_1 (↑)	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}
I_2 (←)	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}
I_3 (→)	n_{31}	n_{32}	n_{33}	n_{34}	n_{35}
I_4 (↓)	n_{41}	n_{42}	n_{43}	n_{44}	n_{45}
I_5 (/)	n_{51}	n_{52}	n_{53}	n_{54}	n_{55}

Table 12: Confusion matrix defined for the joystick.

A unique confusion matrix CM can be presented unifying all available inputs (Table 13).

CM		True						
		I_1	I_2	I_3	I_4	I_5	…	I_N
Predicted	I_1	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	…	n_{1N}
	I_2	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}	…	n_{2N}
	I_3	n_{31}	n_{32}	n_{33}	n_{34}	n_{35}	…	n_{3N}
	I_4	n_{41}	n_{42}	n_{43}	n_{44}	n_{45}	…	n_{4N}
	I_5	n_{51}	n_{52}	n_{53}	n_{54}	n_{55}	…	n_{5N}
	…	…	…	…	…	…	…	…
	I_N	n_{N1}	n_{N2}	n_{N3}	n_{N4}	n_{N5}	…	n_{NN}

Table 13: General confusion matrix.

For each input device confusion matrix it is possible to calculate the recall and precision of each input.

Definition 10: The **recall of each input** is defined as the probability of a true input being correctly classified and can be calculated as:

$$rec_i = \frac{n_{ii}}{\sum_{m=1}^{N} n_{mi}} \qquad \textbf{(Eq 45)}$$

where n_{mi} is the number of times that I_i is recognized as I_m and N the number of inputs.

Definition 11: The **precision of each input** is defined as the probability of a predicted input represents that true input and can be calculated as:

$$prec_i = \frac{n_{ii}}{\sum_{m=1}^{N} n_{im}} \qquad \textbf{(Eq 46)}$$

where n_{im} is the number of times that I_m is recognized as I_i and N the number of inputs.

Basically, precision is the number of correctly identified inputs as a percentage of the total numbers of identified inputs. Recall is the number of correctly identified inputs as a percentage of the total number of inputs available. It is important to refer that in the concrete problem of giving an adapted command language, an extra case representing when other distinct input was predicted, was added in the predicted categories.

It is possible to combine the recall and precision of each input using for example the arithmetic mean or a more adequate measure that uses the harmonic mean called the F-measure [342]. This measure gives high values only when both precision and recall have high values. Definition 12 presents the general definition of the F-measure.

Definition 12: The **$F_{\beta i}$-measure of each input** is defined as:

$$F_{\beta i} = \frac{(\beta^2 + 1) \times prec_i \times rec_i}{\beta^2 prec_i + rec_i} \quad \textbf{(Eq 47)}$$

where $0 \leq \beta < +\infty$ is a parameter that controls the balance between the recall and the precision. If β = 1 then the F-measure is equal to the harmonic mean. If β >1, F is more recall oriented else it is more precision oriented.

Considering the harmonic mean the principal diagonal of matrix (*F*) can represent the F-measure of the inputs as showed in Table 14.

F (Predicted \ True)	I_1	I_2	I_3	I_4	I_5	…	I_N
I_1	F_{11}						
I_2		F_{22}					
I_3			F_{33}				
I_4				F_{44}			
I_5					F_{55}		
…						…	
I_N							F_{NN}

Table 14: F – measure for each input.

4.7.3 Input Device Advisor

The general planning for constructing the IDAS involved several components. Using the information given by the user profile the first component, the simplest one, gives the best choice of the input devices for driving the IW. The supervised tests performed with real patients allowed to define a threshold for the accuracy for each input device (Section 5.1.4). The input device is advised or alternately a sub set of the possible combinations with the set of available input devices {wiimote, gamepad, joystick, microphone for voice commands and BCI for the facial expressions}. In general, there is a total of 2^n-1 possibilities where *n* is the number of the input devices.

The IDAS analyses the overall accuracy, using the F-measure, of each input device in the input device confusion matrix and if the accuracy is higher than a threshold (a value of 30% was used in the experiments, suggested by the specialists and further validated by empirical data) then the multimodal interface alerts the user that the input device is an option for him to test.

4.7.4 Wheelchair Control Advisor

The idea of having an aided control, for each patient, emerged from the experiments with real people with physical constraints. In fact, there were several patients that could have some kind of movement ability, however not precise enough for driving a wheelchair in a safe manner. The aided control was implemented in a simple but effective manner (see Section 4.4.1.3) and the adaptation for each user was performed using the profile module. As in the input device advisor, the wheelchair control advisor provides several alternatives considering the different accuracy levels achieved by the specific user:

- Shared control with an aid level of 100% (with obstacle avoidance) – if the overall accuracy is included in $[0, x[$;
- Shared control with an aid level of 50% (with obstacle avoidance) – if the overall accuracy is included in $[x, y[$ where $0 < x < y < 1$;
- Shared control (with obstacle avoidance) – if the overall accuracy is in the interval $[y, 1[$.

Obstacle avoidance is always advised using shared control, since it increases the safety of the user. In particular, if the accuracy has the value between 30% (x) and 70% (y) then the aided control advised is at a level 50%. If the user selects an input device with very low accuracy, and that was not one of the advised input devices, then the wheelchair control informs that the best choice is to use the aided control at a 100% level.

However, more than the suggestion of the input device that should be used by the individual a command language could also be presented. In fact, the best association of inputs to commands should be presented. The next section presents the proposed methodology and implementation for the derivation of an adapted command language.

4.7.5 Command Language

In order to generate a command language adapted to a given user several points should be taken into account: the time efficiency, the recognition probability of an input sequence and the intuitiveness of an input sequence to be associated to a command. Figure 71 shows the quantifiable criteria used for the command language definition.

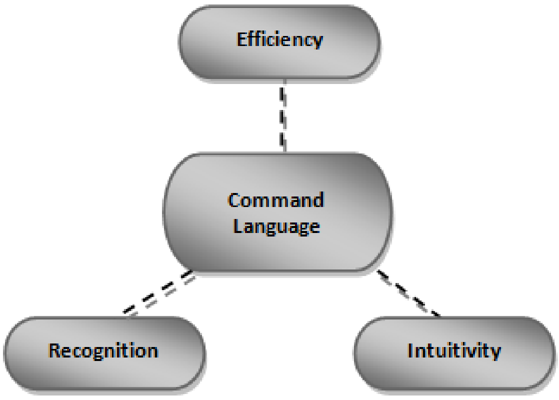


Figure 71: Criteria used for the command language.

Next, these three points are going to be presented in more detail using the formalization of the measurable criteria.

Time and Time Efficiency

Remembering that a sequence of inputs S_i can be formalized as $I^{(i,1)}\ I^{(i,2)}\ I^{(i,3)} \ldots I^{(i,Ni)}$, where each $I^{(i,N_i)} \in \{I_1, I_2, \ldots, I_k\}$ and a single command can be associated to a final sequence that produces an action, the time to generate a command is composed by a component of time to select the inputs and by the time taken to assure that the user does not introduce another valid input that makes the sequence another valid sequence or timeout ($t_{timeout(i)}$). For example the user may introduce the sequence $S = I_1\ I_5$ and there are valid sequences $S_2 = I_1\ I_5$ and $S_4 = I_1\ I_5\ I_4$. Before considering the input as sequence S_2, the system waits timeout to assure that the user does not input also I_4 making the sequence S_4. The total time for a particular command to be used has the Equation 48:

$$t_{S_i} = \sum_{k=1}^{N_i} t^{ID}_{I^{(i,k)}} + t_{timeout(i)} \qquad \textbf{(Eq 48)}$$

where k is the number of each of the inputs used in the sequence, S_i the identification of the sequence i and N_i the total number of the inputs of sequence i. Therefore it is possible to determine the total time for all the commands necessary to drive the intelligent wheelchair:

$$T_C = \sum_{j=1}^{C_j} t_{S_j} \qquad \textbf{(Eq 49)}$$

where C_j is the number of commands in the command language.

The time efficiency can be defined as a function of time, if more time is necessary for a command to be used then that command is less efficient. It is possible to formalize this function as in Equation 50:

$$\begin{aligned} eff &: [0,+\infty[\to [0,1] \\ t_{S_i} &\mapsto \frac{1}{t_{S_i}+1} \end{aligned} \qquad \textbf{(Eq 50)}$$

The total time efficiency is the sum of all the efficiency values of the commands that compose a command language:

$$T_{C_{eff}} = \sum_{j=1}^{C_j} eff\,(t_{S_j}) \qquad \textbf{(Eq 51)}$$

Sequence Recognition

It is also possible to define and calculate the **sequence S_i recognition value**. Assuming the independence of recognition of the different inputs in a sequence, the sequence S_i recognition value is the product of the F-measure values as in Equation 52.

$$regS_i = \prod_{k=1}^{N_i} F_{I^{(i,k)}}^{ID} \qquad \textbf{(Eq 52)}$$

where $F_{I^{(i,k)}}^{ID}$ is the F-measure value in the position of the principal diagonal of the input $I^{(i,k)}$ be in use in the sequence and for a specific input device (*ID*). The total recognition value of a set of commands can be determined by Equation 53:

$$T_{reg} = \sum_{j=1}^{C_j} regS_j \qquad \textbf{(Eq 53)}$$

where C_j is the number of commands in the command language.

Intuitiveness

Another concept that should be analysed is the **intuitiveness** of a sequence of inputs. In order to have values similar to the efficiency and recognition, it was defined that an input sequence, associated to a given action, can have a value of intuitiveness between 0 and 1. The value of 1 means that the input is very typical for performing that command and a value of 0 means that the input typically is associated with an opposite command. For example, if a sequence is composed of a single input such as saying “front” and the action of the wheelchair associated is go forward then the intuitiveness value may be 1. If the same input is associated with the command that makes the IW going back then the intuitiveness will be 0. Table 15 presents an example of the intuitiveness of several voice inputs.

The intuitiveness of a sequence composed by two or more inputs can also be obtained by the product of the intuitiveness of each input. In fact, an example is a sequence composed of two inputs such as say “front” “front” then the intuitiveness in this case it is also 1 when the objective is to drive the wheelchair forward.

Commands	I_1 ("Go")	I_2 ("Left")	I_3 ("Right")	I_4 ("Back")	I_5 ("Stop")	I_6 ("Front")	I_5 ("Forward")
Forward	1	0	0	0	0	1	1
Left	0	1	0	0	0	0	0
Right	0	0	1	0	0	0	0
Back	0	0	0	1	0	0	0
Stop	0	0	0	0	1	0	0

Table 15: Intuitiveness for the voice inputs.

Command Language Implementation

In order to obtain the best performance the command set that maximizes the sequence recognition, the intuitiveness and time efficiency should be obtained.

Basically, a command language adapted to the user should be found that maximizes the function composed by the total time efficiency, total recognition and intuitiveness:

$$\underset{T_{eff}, T_{reg}, T_{\text{int}}}{\arg\max}(\alpha T_{eff} + \beta T_{reg} + \gamma T_{\text{int}}) \quad \textbf{(Eq 54)}$$

where α, β and γ are parameters that could be adjusted. The optimization may be performed by any type of optimization algorithm with emphasis on iterative meta-heuristics such as basic hill-climbing [343], simulated annealing [344], tabu search [345] or genetic algorithms [346].

For the implementation, in order to show the concept, hill-climbing was selected, mainly due to its simplicity, and a modified hill-climbing algorithm was implemented. The pseudo-code and the details of the implementation are subsequently explained. First the user abilities on using several inputs are captured with the profile module and the recognition values are obtained for all the available inputs. The time taken to execute each input sequence is also captured and the efficiency of performing the inputs is calculated. The degree of intuitiveness was indicated initially by the user or by a specialist. Figure 72 details the algorithm implementation.

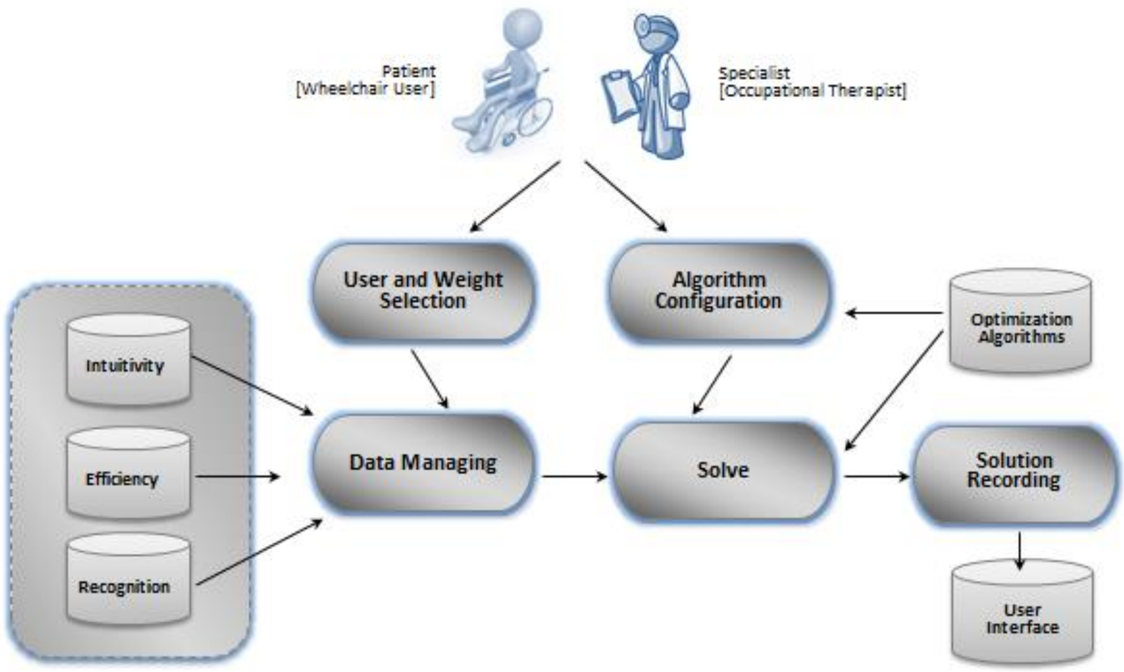


Figure 72: Command Language Advisor Implementation.

The system starts by reading the select user recognition and efficiency data and the intuitiveness data for the set of available inputs and commands. After selecting and configuring the optimization algorithm, the system solves the optimization problem, as previously defined, using a given meta-heuristic and subsequently recording the solution so that it can be used on the context of the multimodal interface. Hill-climbing was selected for performing the experiments on this work. However it is easy to extend the system for using other optimization algorithms such as simulated annealing or genetic algorithms.

The pseudo-code for the optimization process is detailed in Algorithm 1. For this implementation only voice, joystick and wiimote inputs were used. However, the system may be easily extended with further input devices using them exactly as the three included in this version.

The algorithm receives the user name, number of input devices (three on this version: voice, joystick and wiimote inputs), number of available commands and the maximum size for the input sequences. It also receives the algorithm id that enables to consult the algorithm type and parameters. The algorithm outputs a solution that associates to each command an input sequence trying to maximize the evaluation function considered. It also outputs the evaluation value achieved for the best solution found. The solution structure is depicted in Table 16. The solution is basically a matrix of NC commands (for example: "Front", "Left", "Right", "Back" and "Stop") and NS inputs forming the corresponding input sequence used to trigger that command. Each cell of the solution matrix may be NULL (in case the sequence used is shorter than the maximum number of inputs for a sequence NS) or composed by an input device and an input.

Algorithm 1: Command_Language_Advisor(userName, NID, NM, NC, NS, algId), solution, best

```
inputs:
   userName – User name (that enables to consult user characteristics and data)
   NID – Number of input devices. 3 Input devices were used (joystick, voice and wii)
   NM – Maximum number of inputs per input device. It includes (NV, NJ, NW)
        as the maximum number of Voice Inputs, Joystick Inputs and WIImote Inputs
   (NC, NS) – Number of available commands and maximum of Inputs in a sequence
   algId- Algorithm identification enabling to get all algorithm parameters
outputs:
   solution – Solution containing one input sequence for each command
   best -  Best solution evaluation
begin
   id ← getID_usersFile(userName)
   weights = (w_rec, w_time, w_intu) ← readfile_user_weights(id)
   rec = (rec_voi[NV], rec_joy[NJ], rec_wii[NW] ← readfile_recognition(id)
   time = (time_voi[NV], time_joy[NJ], time_wii[NW]) ← readfile_efficiency(id)
   intu = (intu_voi[NC][NV], intu_joy[NC][NJ], intu_wii[NC][NW]) ← readfile_intuit(id)
   alg = (algType, param, maxIter, maxNoImp, neighbourF) ← Readfile_alg(algId)
   solution ← random_solution(alg, (NC, NS), (rec, time, intu))
   best ← evaluate_solution(solution, weights, rec, time, intu)
   currBest ← best
   currSolution ← solution
   it ← 0
   noimp ← 0;
   while it<maxIter ∧ noImp<maxNoImp do
      solNew ← neighbour_solution(neighbourF, currSolution, (NC, NS, NID))
      if repeated(solNew) then
         val ← -∞
     else
         val ← evaluate_solution(solNew, weights, rec, time, intu)
      endif
      if solution_change_criteria(alg, val, best) then
         currSolution ← solNew
         currBest ← val
         noImp ← 0
      endif
      if currBest > best then
         best ← currBest
         solution ← currSolution
      else
         noImp ← noImp + 1
      endif
      alg ← update_alg_parameters(alg, it, currSolution)
      it ← it + 1
   endwhile
   return (solution, best)
end
```

The Command Language Advisor, starts by reading all the input files containing the problem data. This includes consulting the user id, the weights to be used for the recognition, efficiency and intuitiveness (to be used on the evaluation of a given solution). The algorithm also reads the input files containing all the available data concerning the user. This includes the recognition and efficiency vectors for all possible inputs (voice, joystick and wii on this implementation) and the intuitiveness matrix that relates the intuitiveness of using each of the inputs available on the three input types for performing each of the available commands. Finally, the algorithm parameters are read from the algorithm database.

The solving process starts by generating an initial random solution for the problem, composed by a valid input sequence (composed by *1* to *NS* inputs) for each of the possible (*NC*) commands. It then evaluates the solution and saves the solution and evaluation as the best ones of those already tested. The main algorithm cycle is composed by *maxiter* iterations (or *maxnoimp* iterations without improvement). In each iteration, a new solution is calculated, that is neighbour (using the defined neighbouring function) from the present solution. Algorithm 2 displays the simple neighbour algorithm that was used in most of the experiments shown in Section 5.2.5.

Number of Commands (NC=5)

Number of maximum inputs in a sequence (NS=4)		*1*	2	3	4	5
	1	*wii* *2*	*voice* *1*	*wii* *2*	*voice* *1*	*voice* *1*
	2	*NULL*	*joy* *1*	*wii* *3*	*joy* *3*	*joy* *3*
	3	*NULL*	*NULL*	*wii* *1*	*NULL*	*joy* *3*
	4	*NULL*	*NULL*	*NULL*	*NULL*	*NULL*
		Ex: *Front*	*Ex:* *Left*	*Ex:* *Right*	*Ex:* *Back*	*Ex:* *Stop*

Table 16: Command Language Advisor Solution Structure.

Algorithm 2 considers two types of neighbours: (i) changing/adding/removing an input sequence associated to a command; (ii) exchanging the input sequences used for two distinct commands. The algorithm starts by copying the current solution to the new neighbour solution. It then decides which of the neighbour functions will be used (i) or (ii) with a probability of 50% each in the current simple implementation.

For applying neighbourhood (i) a command and an input sequence step are randomly selected until the step to change is a valid step (1 or a step without any valid steps executed after it). If the step to change is the last step and it is not step number 1 (that obviously may not be cleared), a probability of 50% is used to decide on clearing it. If the step is cleared both its input device and input are set to NULL. Otherwise a new valid value is randomly selected for the step input device and input. Neighbourhood (ii) is applied by randomly selecting two distinct commands and then swapping the commands input sequences, step by step. Finally the algorithm returns the new neighbour solution.

Algorithm 2: neighbour_solution(neighbourF, solution, (NC,NS,NID)), newSolution

```
inputs:
   neighbourF – Neighbourhood function number (not used on this simple version)
   solution – Solution containing input sequence for each command
   NC, NS – Number of commands and maximum inputs in sequence
   NID–Number of Input Devices (nInputs(i) gives the number of inputs of an Input Device
outputs:
   newSolution – Neighbour solution considering the neighbourhood function. The solution
           size is NCxNS. Each solution element is composed by two parts an input device
           (between 1 and  NID and an input between 1 and the number of inputs of that
           input device)
begin
   do
      newSolution ← solution
      neighbourType ← random(1, 2)
      if neighbourType=1 then
         ncom ← random(1, NC)
         do
            nseq ← random(1, NS)
         while (nseq ≠ 1 ∧ inputDevice(newSolution[ncom][nseq-1]) = NULL)
         clear← random(0, 1)
         if clear=1 ∧ (nseq ≠ NS ∧ inputDevice(newSolution[ncom][nseq+1]) = NULL ∨
                  nseq=NS) ∧ nseq ≠ 1 then
            inputDevice(newSolution[ncom][nseq]) ← NULL
            input(newSolution[ncom][nseq]) ← NULL
         else
            nInpDev ← random(1, NID)
            inputDevice(newSolution[ncom][nseq]) ← nInpDev
            input(newSolution[ncom][nseq]) ← random(1, nInputs(nInpDev))
         endif
      else
         ncom1 ← random(1, NC)
         do
            ncom2 ← random(1, NC)
         while (ncom1 = ncom2)
         for nseq=1 to NS do
            swap(inputDevice(newSolution[ncom1][nseq]),
                  inputDevice(newSolution [ncom2][nseq]))
            swap(input(newSolution[ncom1][nseq]),
                  input(newSolution[ncom2][nseq]))
         endfor
      endif
   while (newSolution = solution ∨ repeated_sequence(newSolution))
   return newSolution
end
```

The solution is evaluated using the evaluation function considered and if it is better than the best solution found (given the solution change criteria used for the algorithm in use) then it will become the new current solution and the current best will be this solution evaluation. If the solution is better than the best solution already found the best solution (and its corresponding evaluation) will be changed to the current ones.

Algorithm 3: CL_Evaluator – evaluate_solution(solution, weights, rec, time, intu), evaluation

```
inputs:
   solution – Solution containing the input device and inputs used for each input
          sequence for each command
   weights – Weights for recognition, efficiency and intuitiveness
   rec[3][NM] – Recognition matrix containing for each input device and input the
          recognition probabilities for a given user
   time[3][NM] – Time matrix containing for each input device and input the t
          times enabling to calculate efficiency information for a given user
   intu[NC][3][NM] – Intuitiveness matrixes relating each input from each input device
          to a given command for a given user
outputs:
   evaluation – Solution evaluation considering the evaluation function
begin
    (w_rec, w_time, w_intu) = weights
   evaluation ← 0
   for ncom = 1 to NC do
      recVal ← 1
      timeVal ← 0
      intuVal ← 1
      for nseq = 1 to NS do
         inpDev ← inputDevice(solution[ncom][nseq])
         inp ← input(newSolution[ncom][nseq])
         if inpDev = NULL then break
         else
            recVal ← recVal * rec[inpDev][inp]
            timeVal ← timeVal + time[inpDev][inp]
            intuVal ← intuVal * intu[ncom][inpDev][inp]
         endif
      endfor
      evalComm ← w_rec* recVal + w_time*1/(timeVal+1) + w_intu*intuVal
      evaluation ← evaluation  +  evalComm
   endfor
   return evaluation
end
```

The command language evaluator algorithm (Algorithm 3) uses the pre-defined weights and the recognition, efficiency and intuitiveness user information to evaluate the current command language. It starts by initializing the evaluation to 0. Then, for each command in the solution it evaluates the input sequence used for that command given its recognition, efficiency and intuitiveness and the corresponding weights considered.

Each input sequence is evaluated until its end (and thus if a NULL value is encountered meaning the end of the input sequence its evaluation will be finished). For the recognition and intuitiveness, products of the corresponding values of the inputs on the sequence are used. For the efficiency, first the total time of the sequence is calculated and then Equation 49 is applied. On this algorithm version only commands without the need for timeout are considered and thus timeouts are not added.

The solving algorithm (Algorithm 1) final step consists on returning the solution found and its evaluation. The solution may then be used by the multimodal interface for enabling the user to drive the Intelligent Wheelchair.

4.8 Conclusions

This chapter presented the methods implemented in order to be able to perform user profiling extraction and to adapt the interfaces to the user, giving them the best way for driving the IW. The chapter presented the proposed multimodal interface, the *IntellSim* which is the simulator, essential to test the IW in a realistic way, the wheelchair control methods, the multimodal data gathering system, the user profiling methodology and finally the data analysis system.

The experiments to validate the system were performed in an iterative manner. Based on the experience gained during the development of the first multimodal data gathering system and the first set of experiments with the IW prototype, the data analysis system was developed including the methods for user profiling enabling to rapidly obtain valid information about the user. This allowed the realization of a second round of experiments with real users suffering from cerebral palsy starting by using the user profiler to extract valid information about their characteristics and then using the data analysis system to decide the best driving methodology for each of them.

The system developed and described on this chapter, based on the multimodal data is capable of extracting the most relevant information from the patient and environment allowing to have adapted controls that can in fact help the user in driving the intelligent wheelchair. All the system modules were tested and verified with experiments involving a set of users without any disability and also a set of real users suffering from severe mobility constraints as demonstrated in the next chapter.

Chapter 5

5. Experiments and Results

This chapter presents the description of all experiments performed to validate the proposed methodology. The approach was inspired in the CRISP-DM standard [171] where the first phase was very relevant. In fact, the first step was the understanding phase, focusing on understanding the project objectives from a human perspective, considering the usability, autonomy and independence of the users when driving the IW. Then this knowledge was converted into the problem definition, and then a preliminary plan was developed to achieve the specified objectives. In this phase of understanding a set of preliminary experiments were designed and a set of objectives were determined. Most of the results of the experiments were determined analysing the IW driving performance of the user in real and simulated environments. The users' opinions were obtained through questionnaires with a validated scale of usability.

The first objective of the experiments was to test the integration of the multimodal interface with the previously work developed in the IntellWheels project. A second objective was to test the possibility of using a simulator to perform the experiments and compare it with the real prototype.

After these tests, a new simulator was developed to achieve higher realism to perform the following experiments. Several manual control mappings were also tested. This mapping determines the response behaviour of the wheelchair to the user manual control. The multimodal data gathering system was also tested with a group of users to verify if every variable was correctly recorded.

A plan was drawn and the concept of user profiling with simple but relevant tasks was developed. The user profiling was initially tested with real patients with cerebral palsy and the tasks were tuned for the final experiments.

Statistical analysis helped in the phases of data understanding, preparation and organization for the final experiments. The data analysis system allowed the test of the adapted interface to multiple users with distinct disabilities and a set of final experiments allowed the evaluation and the final deployment of the data analysis system.

The information gathered about the users was included in the next sections. It is important to emphasize that the experiments involved cerebral palsy patients classified with the degrees IV and V of the Gross Motor Function (the highest) and groups of people without severe constraints.

5.1 Module's Validation Experiments and Results

This section presents an evaluation of the results achieved by the system specification and by the implemented prototype. To test the integration of the multimodal interface with the previously developed IntellWheels Platform, two different test scenarios were prepared. The purpose of the first experiment was the evaluation of the multimodal interface performance using the IWP simulator. The second test scenario asked the users to perform tasks similar to the ones used in the first scenario but this time using the IntellWheels wheelchair prototype on a real environment [4].

5.1.1 Multimodal Interface in Simulated and Real Environments

The experiments with the multimodal interface were performed firstly in a simulated environment using the first IntellWheels simulator and then in the real environment. The details of these experiments, the achieved results and the conclusions drawn are presented in the next subsections.

5.1.1.1 Experiments

The first experiment involved 43 students of the Physiotherapy degree at the School of Health Technology of Porto. There, a simulated scenario with part of the school was recreated, and a specific route was traced (using the first IntellWheels simulator). Figure 73 illustrates the 2D representation of the complete route and Figure 74 shows the 2D and 3D representation of the first simulator.

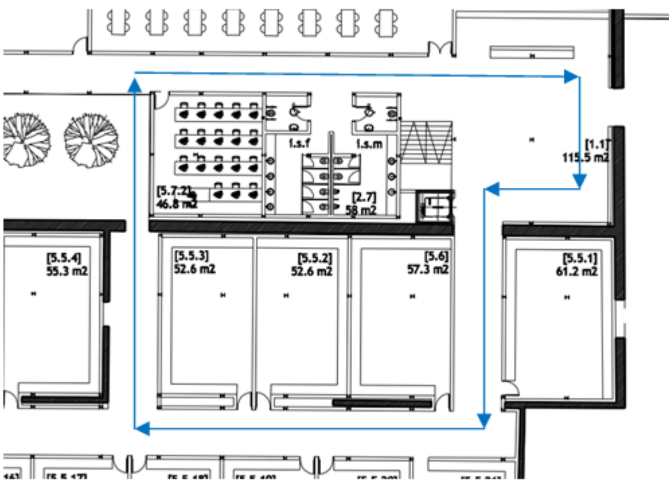


Figure 73: Map of the route for the simulated experiment.

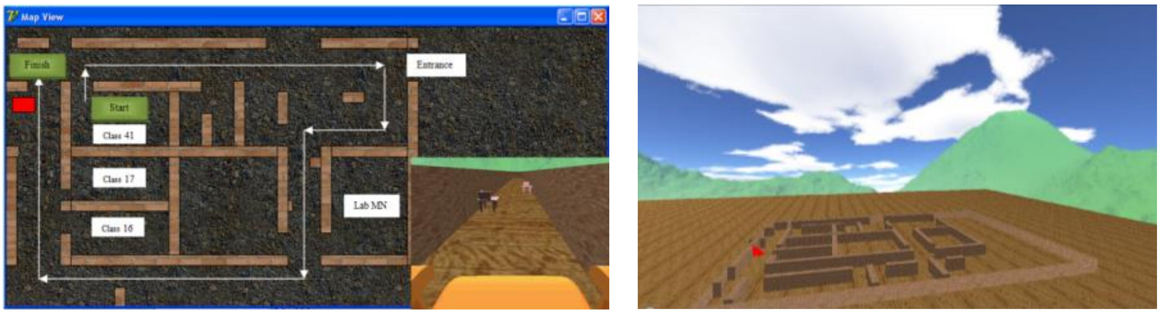


Figure 74: Map of the route in the 2D and 3D representation of the first simulator.

The characteristics of the sample integrated in this preliminary test were important since the users on the sample were very sensitive, due to their academic background, to the questions regarding Intelligent Wheelchairs' usability. Their feedback was important to improve not only the already developed work, but also for proposing improvements and future features that might better assist disabled individuals. Figure 75 shows an example of a test day using the simulator.

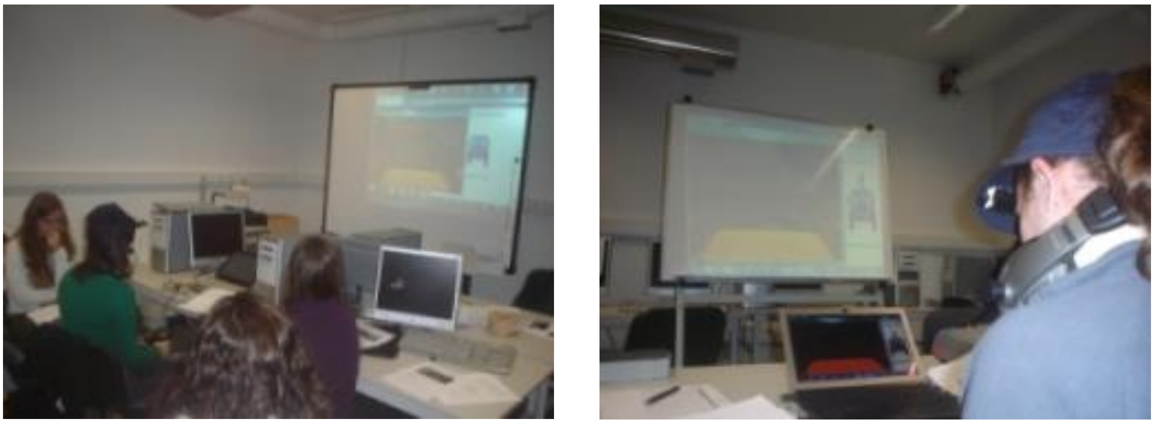


Figure 75: Experiments using the 3D simulator.

The main goal of this pilot test was to attain the performance and efficiency of using different input modalities, integrated in a multimodal interface, to drive an IW and also evaluate the overall behaviour of the IMI. The intention was to detect the existence of possible problems, faults and inconsistencies of the IMI, based on the students' feedback. The methodology applied was the gathering of opinions using a questionnaire that incorporates the System Usability Scale (SUS) [340] which is a simple ten-item *Likert* scale giving a global view of individual assessments of usability [340].

Several different ways of driving the IW through the route were defined: using the gamepad joystick in manual mode; using the gamepad buttons in high-level mode; with head movements (Wii controller); with voice commands; having the freedom to choose any type of input (gamepad, voice, head movements). Since none of the users had any type of previous contact with the IntellWheels project, the first step was to provide an explanation of the main characteristics of the IMI, the type of output actions provided by the IWP control module and the global goals of the experiment.

The second experiment took place at the Faculty of Engineering of the University of Porto. The goal was to evaluate the performance of the IMI using the real wheelchair. This experiment included the participation of 12 volunteers.

Figure 76: Experiments with the real IW prototype.

Table 17 contains the input sequences that were used in this experiment.

Output action	Button input sequence	Voice input sequence
Go Forward	GB1	"Go Forward"
Go Back	GB3	"Go Back"
Right Turn	GB2	"Turn Right "
Left Turn	GB4	"Turn Left "
Right Spin	GB6	"Right Spin"
Left Spin	GB5	"Left Spin"
Stop	GB7 or GB8	"Stop"
Manual mode using GJ	GB9	"Manual mode joystick"
Manual mode using WM	WB ‘A’	"Manual mode wiimote"

GB – Gamepad Button; WB – Wiimote Button; GJ – Gamepad Joystick; WM – Wiimote head movements

Table 17: Input sequences used for the experiment using the simulated IW

The results about the users’ opinions concerning the two experiments were determined through the analysis of the answers to the questionnaire. The achieved performance using the different modes for driving the IW was measured taking into account the time, number of collisions and total average deviation error from the given "ideal" trajectory relatively to the desired trajectory. The time for both experiments was measured by a chronometer. The number of collisions for the first experiment was collected through the simulator logs, whereas for the second experiment this number was collected by an observer. In the first experiment, the measurement of the distance between the real and ideal trajectories was calculated applying the Euclidean distance of a point to a line segment. In the second experiment, the distance between the IW from the ideal trajectory was achieved using Ubisense technology [347], which provides real-time location tracking.

5.1.1.2 Results

The overall results about the experiments with the multimodal interface are in Table 18. The answers and the performance results obtained in the two experiments were analysed and some interesting conclusions were obtained.

	Simulated Environment (n=43)					**Real Environment (n=12)**				
	Mean	**Median**	**Std**	**Min**	**Max**	**Mean**	**Median**	**Std**	**Min**	**Max**
User Identification										
Age	21.12	20	2.29	19	30	24.58	23.5	5.99	20	40
Weight (kg)	60.44	58	9.90	40	91	69.25	65.50	11.10	53	88
Height (cm)	164.84	165	6.283	150	182	173.75	172.5	11.07	159	194
Education level	--	BSc	--	BSc	BSc	--	MSc	--	BSc	PhD
Freq play per week	--	Rarely	--	Never	Always	--	Stimes	--	Never	Always
Use of Wii controls	--	Rarely	--	Never	Always	--	Stimes	--	Never	Always
Use joysticks	--	Never	--	Never	Often	--	Stimes	--	Never	Always
Usability and Safety										
Score SUS	62.79	65	15.65	20	87.50	76.04	78.75	12.31	55	90
Safety managing IW	--	Agree	--	Dis	SAgree	--	Agree	--	Ind	SAgree
Control of the IW	--	Ind	--	SDis	SAgree	--	Ind	--	Dis	Agree
Easy to drive the IW in tight places	--	Dis	--	SDis	Agree	--	Dis	--	Dis	Agree
The IW do not need to much attention	--	Dis	--	SDis	Agree	--	SDis	--	SDis	Dis
Satisfaction level of Controls of the IW										
Gamepad Joystick manual mode	--	Satis	--	Diss	VSatis	--	Satis	--	Satis	VSatis
Gamepad buttons high level mode	--	Satis	--	VDiss	VSatis	--	Satis	--	Satis	Satis
Voice commands	--	Ind	--	VDiss	VSatis	--	Diss	--	Diss	Ind
Head movements	--	Satis	--	VDiss	VSatis	--	Satis	--	Diss	VSatis
Using all commands	--	Satis	--	VDiss	VSatis	--	--	--	--	--
Multimodal Interface										
Information provide by Multimodal Interface	--	Ind	--	SDis	SAgree	--	--	--	--	--
Performance										
Time (min)										
Gamepad Joystick manual mode	3.82	3.61	1.26	2.42	6.93	4.37	5.02	1.70	2.45	5.65
Gamepad buttons high level mode	3.85	3.25	1.82	2.88	11.65	5.88	4.23	3.96	3.02	10.40
Voice commands	6.75	6.32	2.13	3.08	12.87	6.32	6.38	1.80	4.50	8.10
Head movements	3.73	3.40	1.32	2.52	8.35	4.36	5.25	1.77	2.32	5.50
Using all commands	4.07	3.93	0.97	3.12	6.28	--	--	--	--	--
N of collisions										
Gamepad Joystick manual mode	11.50	3.50	14.86	0	39	4.33	0	7.51	0	13
Gamepad buttons high level mode	6.07	3	8.03	0	28	2.33	1	3.22	0	6
Voice commands	29.43	28	20.98	4	73	21.67	19	20.13	3	43
Head movements	6.14	2.50	7.80	0	22	3.67	1	5.51	0	10
Using all commands	9.07	4	11.18	0	38	--	--	--	--	--

Error of deviation from the trajectory asked										
Gamepad Joystick manual mode	0.26	0.26	0.10	0.15	0.52	0.20	0.23	0.05	0.15	0.24
Gamepad buttons high level mode	0.23	0.23	0.06	0.13	0.38	0.19	0.19	0.02	0.17	0.22
Voice commands	0.33	0.33	0.08	0.18	0.51	0.28	0.30	0.03	0.25	0.30
Head movements	0.30	0.28	0.11	0.16	0.53	0.27	0.27	0.07	0.19	0.34
Using all commands	0.32	0.26	0.20	0.16	0.95	--	--	--	--	--

Legend: Stimes – sometimes; SDis – strongly disagree; Dis – disagree; Ind – indifferent; SAgree – strongly agree; VDiss – very dissatisfied; Diss – dissatisfied; Satis – satisfied; VSatis – very satisfied

Table 18: Results of the experiments in simulated and real environment

In terms of characterization of the independent samples, the participants have slightly different results in the age, height and weight. Most of the answers concerning previous experience with video games, in both groups, focus on Never or Rarely, showing the students' lack of experience with this kind of devices. The usability mean of the SUS score is higher in the group of the real environment. This result is justified by the realism that may be lost in the simulated environment.

Another relevant aspect is related with the difficulty and attention needed to drive the IW in tight places. In both experiments, most of the participants affirmed attention is needed in order to drive the IW, mainly in tight places. However, participants also stated they felt they had good control of the IW both in the real and simulated environments. The level of satisfaction with the controls has a median of Satisfied (level 4 in a Likert scale of 5), except for the voice inputs. In fact, since this kind of inputs had a latency period, the individuals needed more time to adapt to it in terms of anticipating the order to the actual action of the IW.

	T test (p value)	**Mann-Whitney (p value)**	**Power**
User Identification			
Freq play per week	--	**0.014**	0.43
Use of Wii controls	--	0.076	0.43
Use joysticks	--	**0.002**	0.43
Usability and Safety			
Score SUS*	**0.009**		0.32
Safety managing IW	--	0.420	0.43
Control of the IW	--	0.223	0.43
Easy to drive the IW in tight places	--	0.058	0.43
The IW do not need to much attention	--	0.359	0.43
Satisfaction level of Controls of the IW			
Gamepad Joystick manual mode	--	0.066	0.43
Gamepad buttons high level mode	--	**0.000**	0.43
Voice commands	--	0.997	0.43
Head movements	--	0.170	0.43

Note *: The p values were calculated with SPSS 19.0 and the Power achieved with G*Power 3.1.2. The Kolmogorov-Smirnov test was applied for the independent sample t test (p $value_{simulated}$ = 0.079 and p $value_{real}$ = 0.200) and the Levene test (p value = 0.009) in which it was assumed the equality of variances.

Table 19: Comparisons of the experiments in simulated and real environment

The information provided by the multimodal interface was mostly classified as Indifferent. The performances on time, number of collisions and error from the “ideal” trajectory using the several commands are worst in the case of voice commands by the same reason related to the latency period previously referred. These differences were analysed from the point of view of their statistical significance. For that, a significance level of 0.05 was considered. The statistical tests used were independent samples *t* test and the non-parametric test Mann-Whitney when the assumptions (type of dependent variable; samples dimension or if the dependent variable is approximately normally distributed within each independent sample) where not fulfil to apply the *t* test. Table 19 shows the p values and the tests’ power for a medium effect size of 0.5.

The results presented in Table 19 show statistical evidences to affirm there are differences between the simulated and real environments in terms of the SUS score. The experiment in using commands such as joystick and level of satisfaction using gamepad buttons in high level also produce statistical evidences of being different. The usability result for the experiment using the real IW is higher since the perception of the environment while driving the IW is also higher when compared to the simulated environment.

5.1.1.3 Conclusions

The first set of experiments allowed having usability score information about using the simulator as a tool to perform the experiments with potential users of an IW. The study of the results, concerning the usability score, showed that there are statistical evidences to affirm that there are differences between the simulated and real environments. For that reason some adjustments and developments were performed in order to have higher realism in the simulated environment. With these experiments it was also possible to conclude that the usability in using the IW in real and simulated environments is satisfactory and it is important to notice that this sample does not need any kind of assistive technology. Other important evidences were that voice commands were too slow and that the Gamepad joystick design was not adapted to this task, since the average number of collisions was greater than expected. The voice commands should be smaller and the joystick should have a design more adapted to users. These adaptations were executed in the following experiments.

5.1.2 Wheelchair Manual Control

The mapping of joystick positions to individual wheel speed determines the response behaviour to manual control. Six of these mappings, described in Section 4.4.1.1 were implemented and tested (now with a bigger joystick). The usability level was achieved based on users’ feedback after testing the different mappings. All the experiments were developed using the new *IntellSim* simulator presented Section 4.3. In the next subsections the conducted experiments and achieved results are presented. The conclusions of these experiments are also described.

5.1.2.1 Experiments

The control algorithms, described in Section 4.4.1.1, were tested with real users, in a simulated environment, in order to verify the usability of the different mappings [11]. A circuit was developed using the *IntellSim* simulator. Figure 77 shows the overall circuit.

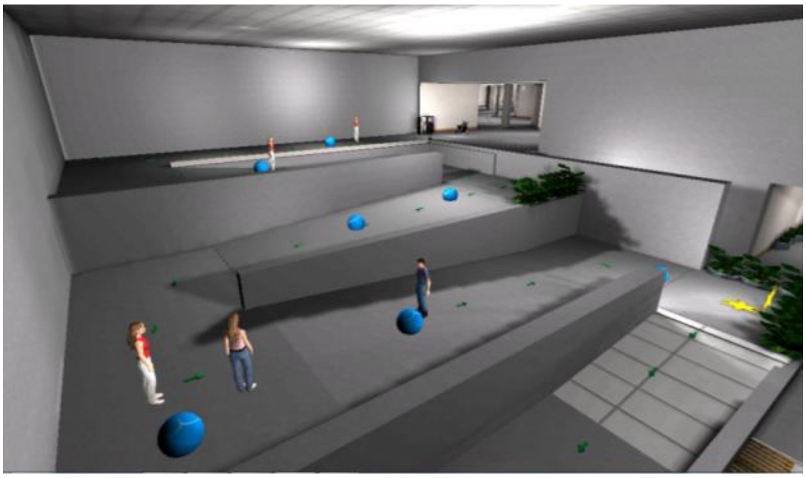


Figure 77: Circuit used for testing the manual controls.

As mentioned before, a serious game was created for this purpose. The game objective was to follow a specific track collecting eight blue balls and at the end a yellow star. Green arrows indicate the route and the blue balls were obligatory checkpoints, since they could be collected by passing near them and each collected ball improves the game score. The virtual people added to the environment were dynamic obstacles that should be avoided.

A quasi-experimental study was performed. The volunteers had an explanation of the purpose of the study and signed the inform consent (Annex F). Figure 78 shows some individuals performing the manual control experiments.

Figure 78: Manual control experiments.

Users were asked to fill a questionnaire composed of four parts: user identification; experience with videogames and joysticks; questions adapted from the Computer System Usability Questionnaire (CSUQ) [341] for each tested option and a final question about the preference order of the tested options. The questions from the CSUQ were measured in a *Likert* scale in order to obtain a final score from 0 to 100. The questions were:

- Overall, I am satisfied with how easy it is to use this control.
- It was simple to use this control.
- I can effectively complete this task using this control.
- I am able to complete this task quickly using this control.
- I am able to efficiently complete this task using this control.
- I feel comfortable using this control.
- It was easy to learn to use this control.
- Whenever I make a mistake using the control, I recover easily and quickly.
- Overall, I am satisfied with this control.

Two more specific questions were asked:

- I felt I had control of the wheelchair.
- It is easy to drive the wheelchair in narrow spaces.

The first sample was composed of 25 able individuals and they drove the simulated wheelchair with the six alternatives of joystick mappings: the algorithms A, B, C that are respectively the Original Mapping, Proportional and Intuitive Mapping, and also with all of them using the quadratic function described in the Section 4.4.1.1 (D, E and F respectively). The order of the experiments was randomly set to avoid the bias relative to the experience of the user. After each round the volunteers answered to several questions related to their experience using the tested mapping.

In a second phase the same experiment was executed with 8 cerebral palsy patients in order to have feedback from real wheelchairs joysticks' users.

5.1.2.2 Results

The first set of experiments was conducted with users without any kind of physical constraints. Some individuals with cerebral palsy also gave their opinions after the same set of experiments.

Users Without Constraints

The sample of 25 able individuals is characterized by having a mean age of 33 years old, with 4 women and 21 men. The experience using ICT of the users is not considerable high (Figure 79), although there are individuals that have considerable experience with joysticks.

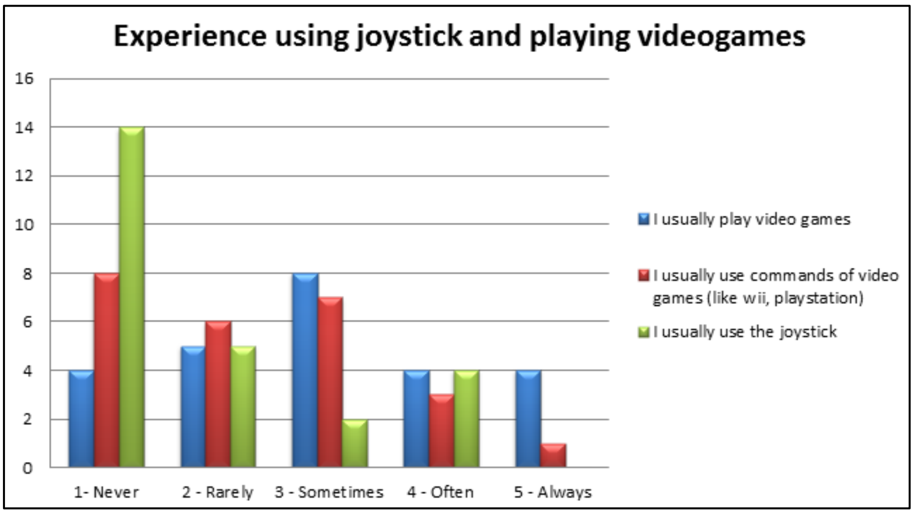


Figure 79: Responses about experience with joystick and videogames.

Table 20 shows the summary of statistical measures concerning the final score for all the mapping options.

	Adapted CSUQ – Final Score					
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Mean	56	63.4	**80.6**	64.6	**72.8**	**77.7**
Median	52.4	58.7	**85.7**	61.9	**76.2**	**82.5**
Std. Deviation	23.6	24.6	17.4	22.7	20.0	17.5
Minimum	22.2	14.3	33.3	25.4	14.3	33.3
Maximum	100	100	100	100	95.2	98.4

Table 20: Summary of statistical measures of the adapted CSUQ score.

The opinions regarding the different joystick mappings indicate that the level of satisfaction is higher when using the option C. The second best option is F, then E, D, B and finally the worst is A.

To confirm that the mapping alternatives are significantly different the statistical Friedman test (related samples Friedman's test two way analysis of variance by ranks) was applied to the final score. The level of significance used was 0.05. With a p value of 0.001, lower than the level of significance, it is possible to conclude that there are statistical differences between the distributions of the scores. To identify which commands are significantly different it was necessary to use a multiple comparison of means of orders (Fisher's least significant difference (LSD)). Table 21 shows the p values of the multiple comparisons, using the Fisher's least significant difference (LSD).

Multiple Comparisons LSD – Adapted CSUQ Score (p values)					
	A	***B***	***C***	***D***	***E***
B	0.199	--	**--**	--	**--**
C	**<0.001**	**<0.001**	**--**	--	**--**
D	**0.022**	0.308	**0.001**	--	--
E	**0.002**	0.064	**0.012**	0.399	--
F	**<0.001**	**<0.001**	0.424	**0.011**	0.085

Table 21: Multiple comparisons of the adapted CSUQ score.

It is interesting to verify that the score of option C is statistically different (using a level of significance of 0.05) of all other options except F. Also, there are not statistical evidences to affirm that the distribution of scores F and E are different.

The results about the score are also confirmed with the order of preference as can be observed in Table 22.

Order of preference (1- Best to 6- Worst)						
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Median	5	5	**2**	4	**3**	**2**
Minimum	1	1	1	1	1	1
Maximum	6	6	5	6	6	6

Table 22: Summary statistics about the order of preference.

The questions regarding the specific behaviour during gameplay have their answers distribution in Figure 80 and Figure 81 for each tested option.

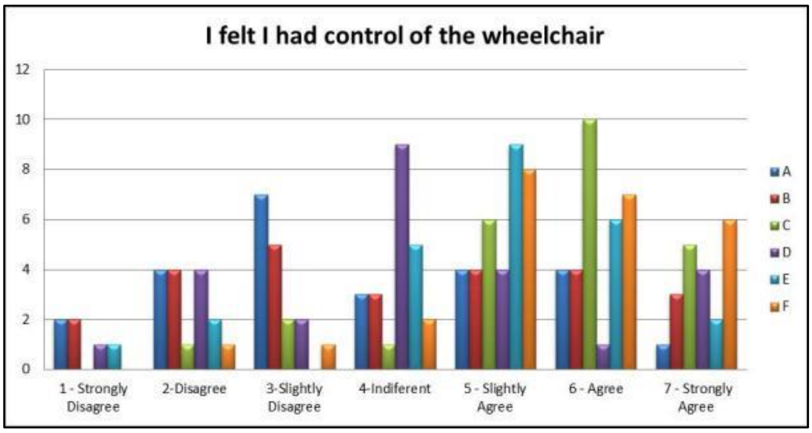


Figure 80: Responses about the feeling of control when driving the wheelchair using the different options.

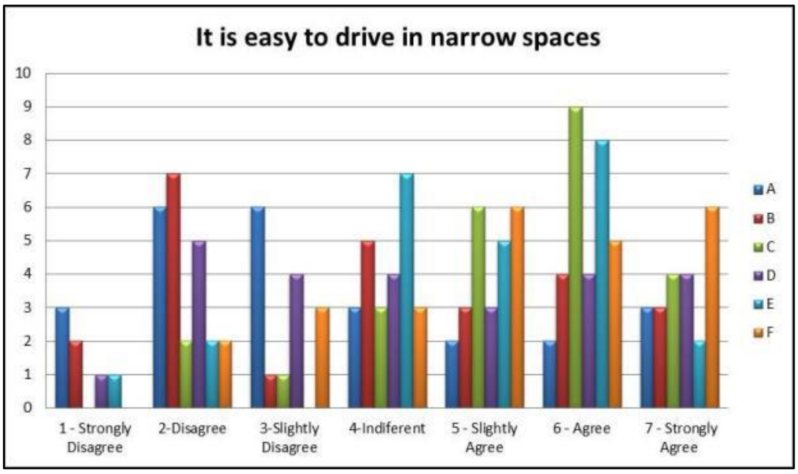


Figure 81: Responses about the experiment when driving in narrow spaces.

The feeling about control of the wheelchair is more visible using the options C and F (the median for the order of preference was 2 for both options). In terms of easiness of driving the wheelchair in narrow spaces, the control F had more responses as “Strongly Agree”. To confirm that the controls are significantly different the statistical Friedman test was also applied to the variables “Feeling about control of driving the wheelchair” and “easy to drive in narrow spaces”. The obtained p values were also less than 0.001, so there are statistical differences between answer distributions of among each joystick mappings in terms of feeling about control of the wheelchair and how easy it is to drive in narrow spaces. The same multiple comparison of means of orders analysis was performed. Table 23 and Table 24 show the corresponding p values.

Multiple Comparisons LSD – Feeling of control (p values)					
	A	***B***	***C***	***D***	***E***
B	0.263	--	**--**	--	**--**
C	**<0.001**	**<0.001**	**--**	--	**--**
D	0.308	0.919	**<0.001**	--	--
E	**0.004**	0.068	**0.012**	0.054	--
F	**<0.001**	**<0.001**	0.919	**<0.001**	**0.009**

Table 23: Multiple comparisons of the feeling about controlling the wheelchair.

The feeling about having control of the wheelchair using options C and F is statistically different with all other options except with each other.

Multiple Comparisons LSD – Ease of driving (p values)					
	A	***B***	***C***	***D***	***E***
B	0.223	--	**--**	--	**--**
C	**<0.001**	**<0.001**	**--**	--	**--**
D	**0.023**	0.281	**0.008**	--	--
E	**0.006**	0.112	**0.032**	0.606	--
F	**<0.001**	**0.001**	0.814	**0.016**	0.056

Table 24: Multiple comparisons of ease of driving the wheelchair in narrow spaces.

The question about driving the wheelchair in narrow spaces with the six options also had p values less than 0.05. In this case the option C is also statistically different from all other options except with F.

Users Suffering from Cerebral Palsy

In order to verify these results with real wheelchair users, patients suffering from cerebral palsy that use joysticks daily to drive their wheelchairs were also invited to test all the control algorithms. This sample is characterized for having five males and three females, with a mean age of 29 years old. All had experience with the joystick of their electric wheelchair although the experience with video games was low, except in one case that answered always play videogames.

Table 25 shows the summary of statistics measures about the final score for all the mapping options.

Adapted CSUQ – Final Score						
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Mean	72.8	77.9	**88.7**	86.7	**84.9**	**83.9**
Median	81.7	88.1	**99.2**	96.0	**98.4**	**99.2**
Std. Deviation	27.7	28.2	19.8	20.6	23.5	24.5
Minimum	30.2	25.4	46.0	41.3	36.5	39.7
Maximum	100	100	100	100	100	100

Table 25: Summary of statistical measures of the adapted CSUQ score – CP patients.

The opinions regarding the different joystick mappings and regarding the mean and median values indicate that the level of satisfaction is higher when using options C and F. The next options are E, D, B and finally A. The Friedman test (related samples Friedman’s test two way analysis of variance by ranks) was applied to the final score. The obtained p value was 0.284, hence there are not statistical evidences to affirm that the distributions of the scores are significantly different (at a level of 0.05).

Nevertheless the results about the score also confirm the tendency to the order of preference as can be observed in Table 26. The median of the preferences shows that options F and C are preferred.

Order of preference (1- Best to 6- Worst)						
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Median	4	4	**3**	4	4	**2**
Minimum	2	3	1	1	1	1
Maximum	6	5	6	6	6	6

Table 26: Summary statistics about the order of preference – CP patients.

The questions regarding the specific behaviour during gameplay have their answers distribution in Figure 82 and Figure 83 for each tested option.

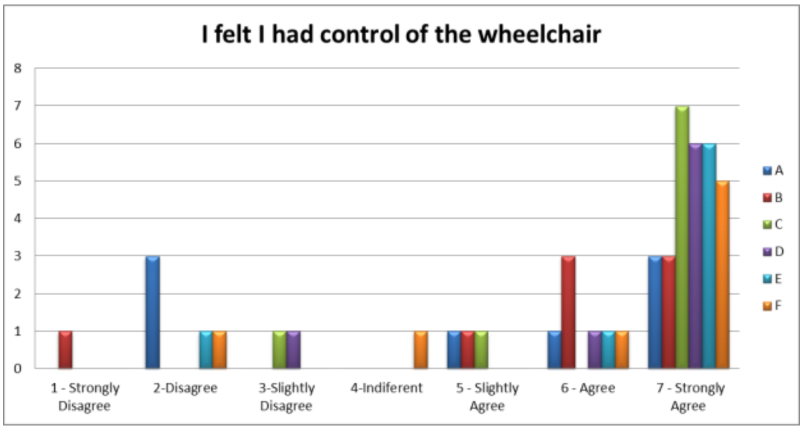


Figure 82: Responses about the feeling of control when driving the wheelchair using the different options – CP patients.

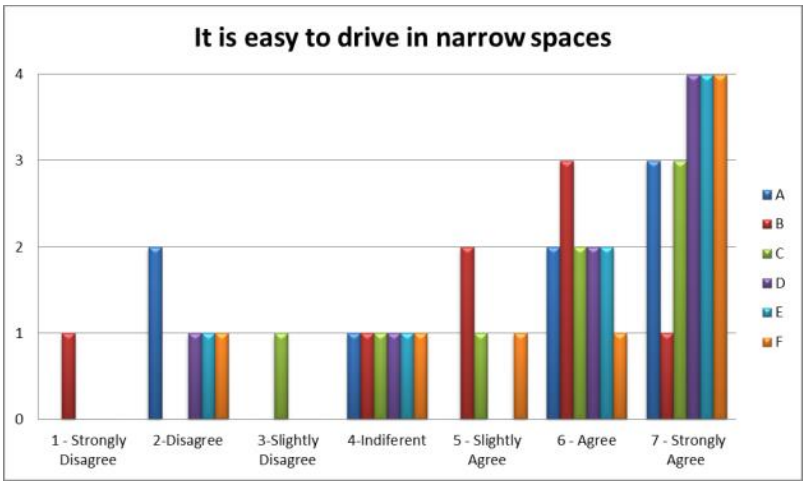


Figure 83: Responses about the experiment when driving in narrow spaces – CP patients.

It is interesting to observe that the number of answers Strongly Agree about the feeling of control of the IW was higher for option C, with 7 cases. The controls which suffer attenuation are also positively viewed as a good way for controlling the wheelchair. Even when the objective is to drive the wheelchair in narrow spaces the distribution of answers are more positive when using these attenuated controls.

To confirm that the controls are significantly different the statistical Friedman test was applied to the variables “Feeling about control of driving the wheelchair” and “easy to drive in narrow spaces”. In the case of the “feeling about control of driving the wheelchair” the p value obtained was 0.01, so there are statistical differences between the distributions of answers among each joystick mappings. The p value for the second question was 0.631 higher than the significance level therefore there are not statistical evidences that the distributions of answers among each joystick mappings are different in terms of “driving the wheelchair in narrow spaces”. The same multiple comparisons of means of orders analysis was performed for the first question. Table 27 shows the corresponding p values.

Multiple Comparisons LSD – Feeling of control (p values)					
	A	***B***	***C***	***D***	***E***
B	0.389	--	**--**	--	**--**
C	**0.008**	0.058	**--**	--	**--**
D	**0.001**	**0.013**	0.517	--	--
E	**0.006**	**0.046**	0.914	0.589	--
F	**0.028**	0.165	0.589	0.238	0.517

Table 27: Multiple comparisons of the feeling about controlling the wheelchair – CP patients.

The feeling about having control of the wheelchair with the option A is statistically different with all other options except with the option B. The feeling about having control of the wheelchair with the option B is also statistically different from all the other options except F and C, although in this last case the p value is near the significance level which also denotes a tendency to be different.

In general the responses of the cerebral palsy individuals are more positive than the answers of the able individuals. It is also interesting to notice a better attitude to the controls with attenuation. Another interesting result was the preference of the Intuitive Mapping C and F confirming the results achieved with the able people.

5.1.2.3 Conclusions

After the first experiments a new simulator was developed (*IntellSim*). In order to enable having meaningful data on the user experiences driving the wheelchair with joystick in the simulated environment, the users should feel confident on their wheelchair controllability. A setup was implemented to select the best way to map the signal of the joystick to the controlled behaviour of the wheelchair. The results demonstrated evidences that options C and F are better for the manual control of the wheelchair. In terms of absolute order of preference option C was used for the final experiments. Thus the conducted study showed that the intuitive mapping method achieved was preferred by the majority of the users. Using this method, users could keep the control of the Intelligent Wheelchair while also being able to control it, even in narrow spaces.

5.1.3 Wheelchair Shared Control

The experiments with the shared control aimed at testing how the users with cerebral palsy would react when having a control that helps them in the task of driving the wheelchair. The usability level was determined based on users' feedback after testing the different shared controls without previously knowing the control characteristics: aided control at a 100%, aided control at a 50% and manual with obstacle avoidance. In the next subsections the experiments, the achieved results and conclusions are presented.

5.1.3.1 Experiments

The experiments were conducted using the *IntellSim* and the order of tests with the shared controls was set randomly. The circuit was the same as in the experiments with the wheelchair manual control, however the number of blue balls was higher since the balls determine the path that the wheelchair should follow.

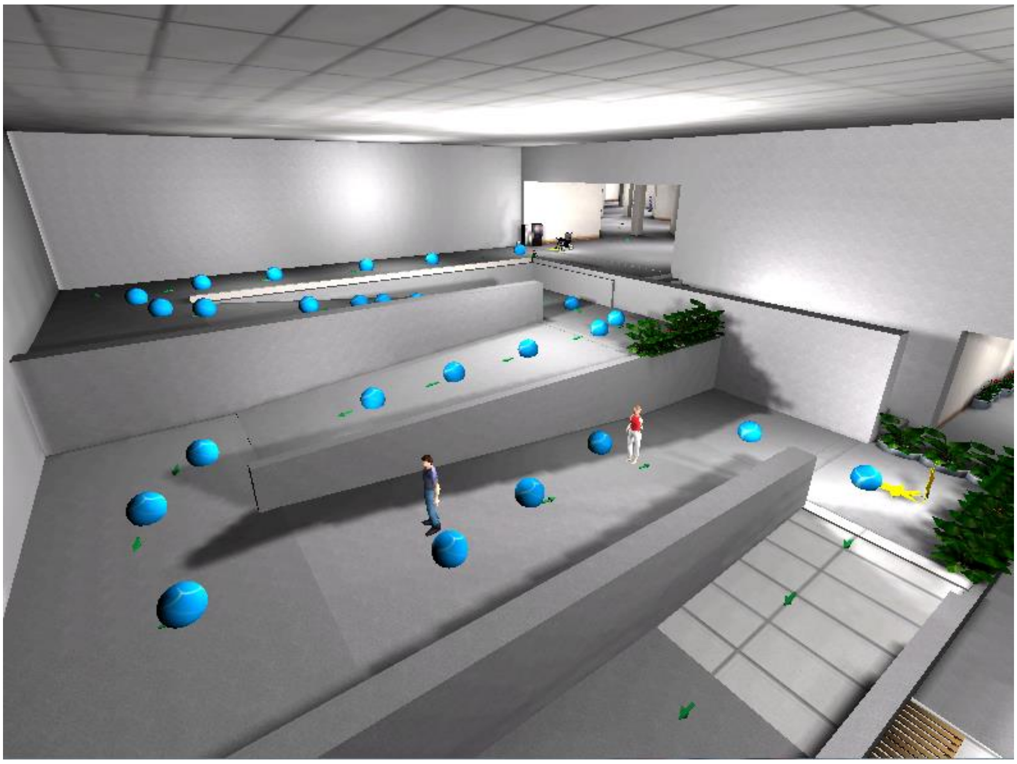


Figure 84: Circuit for testing the shared controls.

The patients tested the shared controls using the joystick as input device and, in different rounds, using head movements, detected using a wiimote. After each round the patients also answered to the same questionnaire as in the experiments with the wheelchair manual control composed of four parts: user identification; experience with videogames and joysticks; questions adapted from the Computer System Usability Questionnaire (CSUQ) [341] for each tested option and a final question about the preference order of the tested options.

The sample was a group of 8 cerebral palsy patients with the level IV and V of the Gross Motor Function Measure.

5.1.3.2 Results

This sample is characterized by having six males and two females, with a mean of age of 31 years old. All had experience with the joystick of their electric wheelchair although the experience with video games was low, except in one case that answered always play videogames.

Table 28 shows the summary of statistics measures about the final CSUQ score for all the mapping options.

Adapted CSUQ – Final Score						
		Joystick			***Wiimote***	
Statistics	***Aided control 100%***	***Aided control 50%***	***Obstacle Avoidance***	***Aided control 100%***	***Aided control 50%***	***Obstacle Avoidance***
Mean	82.7	**87.1**	84.1	76.0	**76.4**	50.6
Median	88.9	**99.2**	88.9	84.9	**91.3**	41.3
Std. Deviation	21.0	22.3	19.4	24.7	33.1	30.8
Minimum	39.68	36.5	44.4	31.8	15.9	14.3
Maximum	100	100	100	100	100	96.83

Table 28: Summary of statistical measures of the adapted CSUQ score – CP patients.

The obtained results from the final score of the CSUQ show a tendency to consider the aided control at a 50% the best way to drive the wheelchair with the joystick and the wiimote. In general, the opinions considered all options very useful except in the case of the head movements with obstacle avoidance which had the worst result. Nevertheless it is possible to affirm that the cerebral palsy patients would react favorably when having a control that helps the driving of the wheelchair.

In order to confirm the differences between the shared controls using joystick and wiimote, the Friedman test (related samples Friedman's test two way analysis of variance by ranks) was applied to the final scores. The p values were 0.484 and 0.004, and for that reason there are not statistical evidences to affirm that the distributions of the scores are significantly different for the joystick shared controls and there are statistical evidences to affirm that the distributions of the scores are significantly different for the wiimote (head movements) shared control at a level of 0.05.

Table 29 shows the p values of the multiple comparisons, using the Fisher's least significant difference (LSD) in the case of the head movements shared controls.

Multiple Comparisons LSD – Head movements shared controls(p values)		
	Aided control 100%	***Aided control 50%***
Aided control 50%	1	--
Obstacle Avoidance	**0.001**	**0.001**

Table 29: Multiple comparisons of the head movements shared controls – CP patients.

The results of the CSUQ score also confirm the tendency to the order of preference as can be observed in Table 30.

Order of preference (1- Best to 6- Worst)						
		Joystick			***Wiimote***	
Statistics	***Aided control 100%***	***Aided control 50%***	***Obstacle Avoidance***	***Aided control 100%***	***Aided control 50%***	***Obstacle Avoidance***
Median	2	2	3	1	2	3
Minimum	1	1	1	1	2	1
Maximum	2	3	3	2	3	3

Table 30: Summary statistics about the order of preference of the shared controls – CP patients.

The aided control, at any level, was chosen as the best way of driving the wheelchair in the case of using the joystick and when using the wiimote. It was interesting to verify that all the patients found the experience of the aided control very pleasant. The careful observation of the experiments executed by the patients was also performed by the occupational therapists and some interesting notes are important to register. All the users think that they had control of the wheelchair even when they were using the aided control at a level of 100%, except one case that had involuntary movements. He found strange that the wheelchair had such as smooth behaviour and stopped a few times to check if the wheelchair corresponded to his action. Another situation was a case of a patient that had cognitive deficits; the level of motivation was very high when using the shared control at a level 100% and this could be identified by his non-verbal language.

The questions regarding the “feeling of control of the wheelchair” and if it was “easy to drive the wheelchair in narrow spaces” have their answers distribution in Figure 85 and Figure 86.

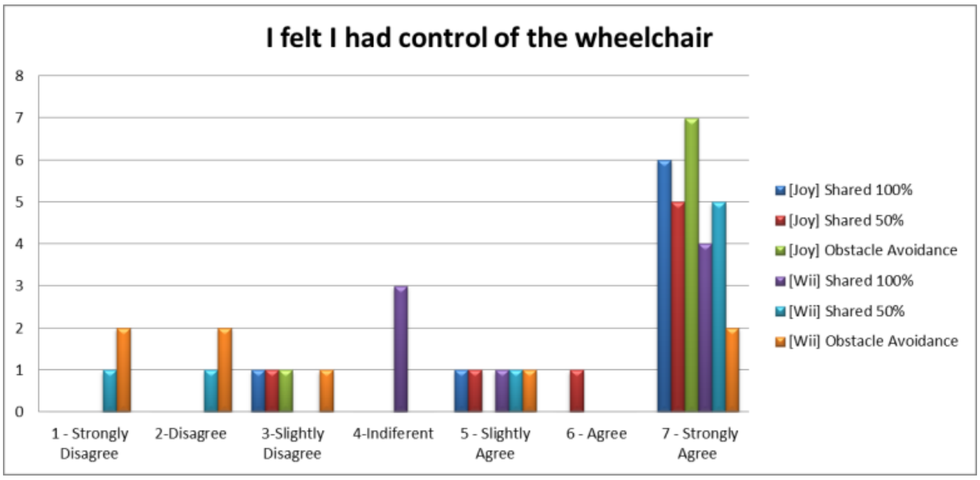


Figure 85: Responses about the feeling of control when driving the wheelchair using the shared controls – CP patients.

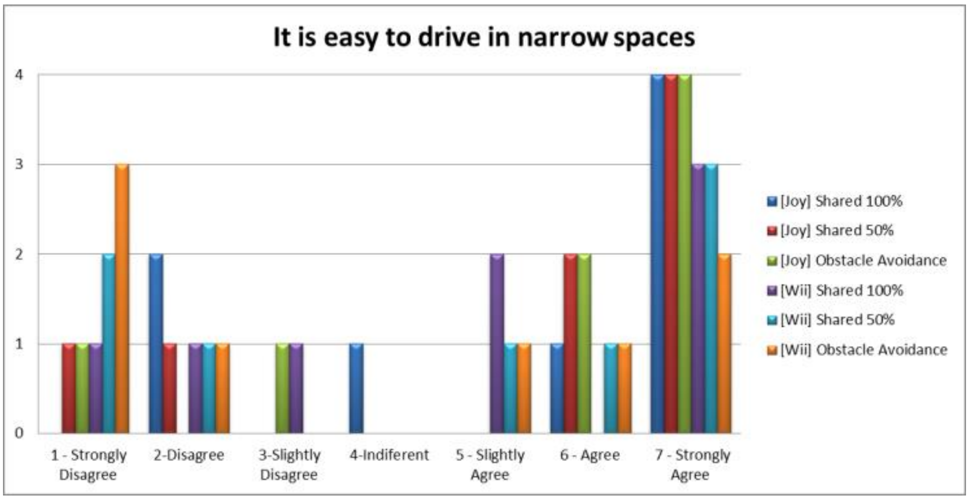


Figure 86: Responses about the experiment when driving in narrow spaces using shared controls – CP patients.

The feeling of control when driving the wheelchair was high for most of the users. The distribution of answers was more disperse when the question about the easiness of driving the wheelchair in narrow spaces. Nevertheless, the tendency is positive except in the cases of driving the wheelchair with the head movements with obstacle avoidance.

5.1.3.3 Conclusions

The shared control experiments revealed that using aided controls for users with severe disabilities are more pleasing. The patients still felt having complete control over the wheelchair movement when using a shared control at a 50% level and thus this control type was very well accepted and should be used in the future. Correcting the direction in case of involuntary movements is also a solution to be considered. Overall the responses were very positive to this kind of control in terms of usability. In this study, the shared control was only used in the simulated environment. However, the future evolution of the project will enable to have the localization issue of the real wheelchair solved in order to allow the aided control also in the real environment.

5.1.4 User Profiling

In the course of this study, the way user profiling is performed was refined several times. The main changes were mainly in the tasks to be performed by the users and in the configuration parameters. This was only possible because several sets of experiments were performed using the profiling module in different phases of the project. Next, the several phases of the process are presented, concluding with the final user profiling setup used in the final experiments of this work.

5.1.4.1 Experiments

The first set of experiments was conducted with users without any kind of physical constraints. Then some changes were performed (as next explained) and several patients suffering from cerebral palsy performed user profiling using the improved version.

Users Without Constraints

The main objective of this experimental work was to make a preliminary study of which are the relevant tasks and what kind of responses received from the individuals could enable to get valid information for improving the user profiling. The first set of experiments involved 33 voluntaries, with a mean age of 24, a standard deviation of 4.2 and without any movements' restrictions.

The first experiment consisted in performing a sequence of tasks with several levels of difficulty. In the first sequence the users needed to push the gamepad buttons GP1 - GP2 (easy difficulty level); the second sequence was GP3 - GP8 (also easy difficulty level); the third sequence was GP5 - GP8 - GP9 (medium difficulty level) and the last sequence was GP6 - GP1 - GP7 - GP4 - GP2 (hard difficulty level due to the number of correct clicks needed to complete the sequence).

The time to perform the buttons' sequences, the average time between clicking on the buttons and the number of errors in pressing the buttons were the main parameters used for analysing the users' performance.

In the experiments with voice commands the individuals had to pronounce the sentences: "Go forward"; "Go back"; "Turn right"; "Turn left"; "Right spin"; "Left Spin" and "Stop" to get the information about the recognition trust level for each voice command.

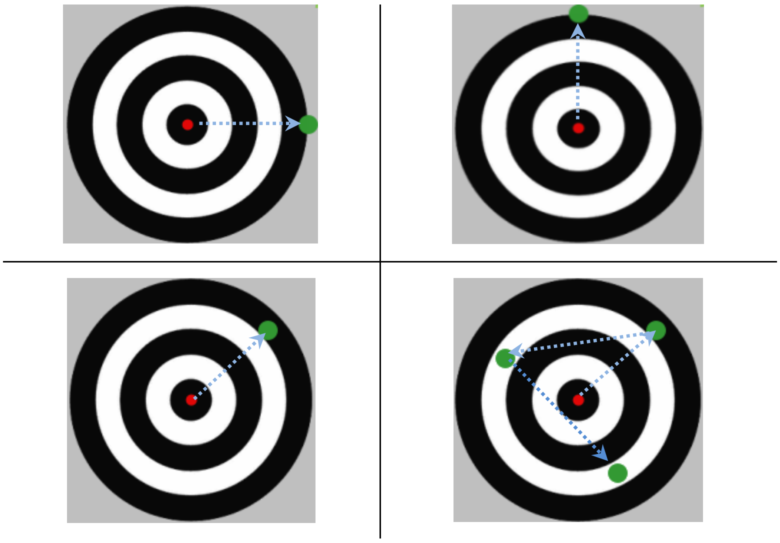


Figure 87: User profiler joystick and wiimote tests.

The last two experiments involved analyzing the control precision of the users control over the gamepad's joystick and of their own head movements using the wiimote. The voluntaries had to move the small dot towards the bigger one represented in the target on Figure 87 with the gamepad's joystick and with the wiimote controller. Figure 87 also shows schematically some of the tasks that were asked to be completed by the users. The required positions to complete the task were: moving right; up; down; northeast; north-west; southeast and a sequence northeast - northwest - southeast without going back to the initial position in the center of the target.

Users Suffering from Cerebral Palsy

The second set of experiments for the user profiling involved users suffering from cerebral palsy. The tests were performed by 34 individuals and the degree of cerebral palsy was classified in the levels IV (23%) and V (77%) of the Gross Motor Function Measure, all require the use of a wheelchair for their locomotion. The mean of the users' age was 28 years old with a standard deviation of 7.7.

The tasks were defined in a similar manner of the previous phase, performed by users without constraints, although some adjustments were applied. The buttons' sequences were slightly different and the joystick of the gamepad was replaced by a large USB joystick, easier to control and manipulate. The sequence tasks were organized with two sequences with an easy level of difficulty pushing the gamepad buttons GP4 - GP2 and GP4 - GP8; the third sequence was GP5 - GP8 - GP9 (medium difficulty level); the third sequence was GP5 - GP8 - GP9 (medium difficulty level) and the last sequence was GP6 - GP5 - GP10 - GP2 (hard difficulty level).

For the experiments with voice commands the individuals had to pronounce the sentences: "Go forward"; "Go back"; "Turn right"; "Turn left"; "Right spin"; "Left Spin" and "Stop" to get the information about the recognition trust level for each voice command.

The experiments involved the control precision of the joystick and the head movements. The users had to move the small red dot towards the bigger one with joystick and with the wiimote controller. Figure 88 shows schematically the tasks that were asked. The positions were moving northeast; up and southwest going always back to the initial position in the center of the target. It was also necessary to be inside the target during three seconds.

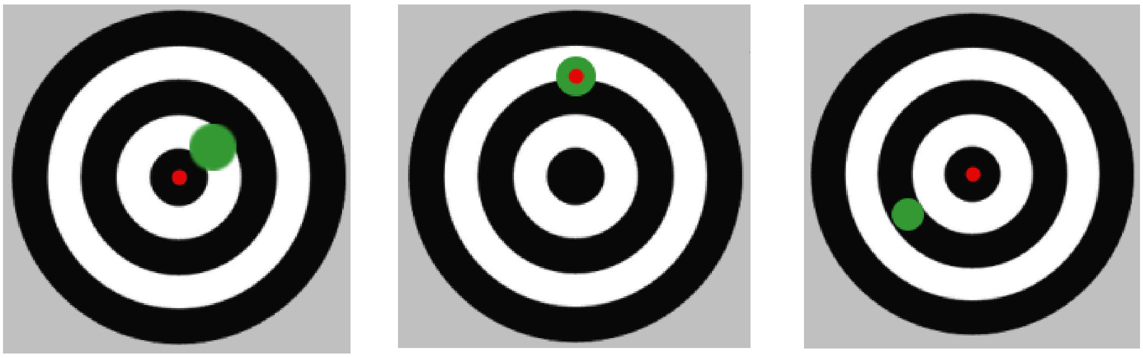


Figure 88: User profiler joystick and head movement tasks.

In this phase facial expressions recognition data was also collected. The facial expressions were assessed with the manager application and the users had to make the correct facial expression while the specialist, at the same time, analyzed the expression made and confirmed in the manager application if the user could do that specific facial expression.

5.1.4.2 Results

The results of these experiments are next presented divided by the kind of users and test set scenario.

Users Without Constraints

In general, the achieved results show a good performance of the individuals using gamepad and voice commands. The behaviour with head movements reflects more asymmetrical and heterogeneous results, since several moderate and severe outliers exist in the time results.

The time consumed to perform the sequences confirmed the growing difficulty of the tasks as it can be seen in Figure 89. In terms of average time between buttons (Figure 90) it is interesting to notice the results for the last sequence. Although it is more complex and longer it has a positive asymmetry distribution. This probably reveals that training may improve the user's performance.

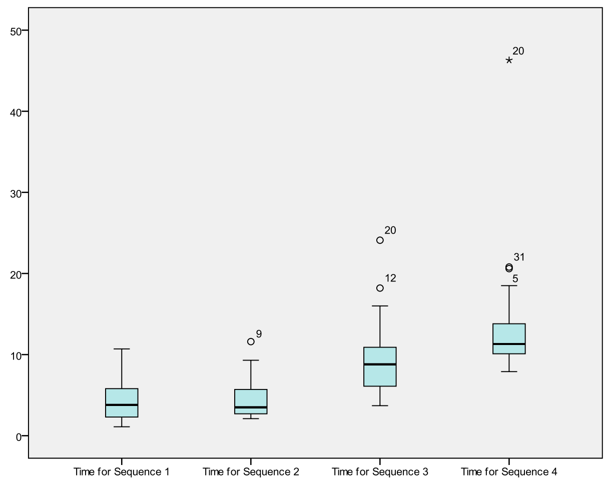


Figure 89: Time to perform the sequences.

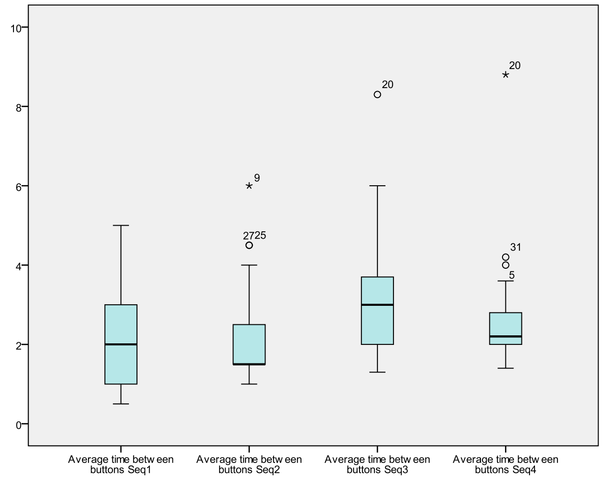


Figure 90: Average time between gamepad buttons.

In terms of number of errors in pressing the buttons (Table 31), the third sequence presents a higher result with at least one fail. The last sequence presented a case where 12 errors were committed.

	Number of Errors							
Seq	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**12**
1	30	1	2	0	0	0	0	0
2	31	2	0	0	0	0	0	0
3	20	7	3	1	1	0	1	0
4	27	1	1	1	0	2	0	1

Table 31: Contingency table with the errors of sequences.

Table 32 presents several descriptive statistics, such as central tendency (mean, median) and dispersion (standard deviation, minimum and maximum), for the trust level of speech recognition.

The speech recognition has very good results. In fact, the minimum of minimums was 82.2 for the sentences “Go Back” and “Stop”. The expression “Go Forward” has the highest mean and median. The sentence “Stop” is more heterogeneous since it has the highest standard deviation (3.85).

Sentence	Mean	Median	S. Dev	Min	Max
“Go Forward”	**95.36**	**95.50**	0.51	93.9	95.9
“Go Back”	94.37	95.00	2.44	82.2	95.9
“Turn Right”	95.31	95.40	**0.42**	94.4	95.9
“Turn Left”	94.76	95.20	1.42	88.4	95.8
“Left Spin”	93.69	94.90	2.88	83.1	95.8
“Right Spin”	94.82	95.00	1.25	89.7	97.2
“Stop”	**92.67**	94.30	**3.85**	82.2	95.8

Table 32: Descriptive Statistics for the trust level of speech recognition.

The paired samples *t* test was applied, with a significance level of 0.05, to compare the means of the time taken to perform the tests using joystick and head movements. The null hypothesis was: the means of time to perform the target tasks with joystick and head movements were equal. The alternative hypothesis is: the means of time to perform the target tasks with joystick and head movements were different. The achieved power was of 0.80 with an effect size of 0.5. Table 33 contains the p values of the paired sample t tests and the 95% confidence interval of the difference.

	95% Confidence Interval of the difference		
Move the red dot to:	**Lower**	**Upper**	**p value**
Right	-2.29	0.67	0.273
Up	-1.38	0.08	0.080
Down	-9.67	-1.87	**0.005**
Northeast	-2.89	0.66	0.211
Northwest	-2.74	-0.17	**0.028**
Southeast	-6.26	1.00	0.150
Northeast - Northwest - Southeast	-5.32	0.37	0.085

Table 33: Confidence intervals of the difference and p values.

Observing the results for the positions Down and Northwest, it is valid to claim there are statistical evidences to affirm that the mean of time with joystick and head movements is different. By using in the same experience joystick and head movements this revealed that the same user may have different performance using these methods.

Users Suffering from Cerebral Palsy

The results of the second phase were interesting since it was possible to understand the difficulties of users with severe movements’ constraints. The tests using the profiling revealed the lack of ability of this group of people in using the joystick buttons. Fine movements are necessary to push the buttons, consequently, to this kind of population, the joystick buttons are not an option. The performed data analysis focuses on the ability in performing the tasks in the profiling and the ability in using input devices for driving the IW.

The speech recognition results show that very few users could use the voice commands in order to drive the IW. The reason for that was partially because of problems with the English language. Table 34 shows the number of users (*n*) that could repeat the asked sentence and the descriptive statistics of the level of speech recognition excluding the missing values.

Sentence	n	Mean	Median	S. Dev	Min	Max
“Go Forward”	9	0.94	0.94	0.008	0.93	0.95
“Go Back”	10	0.93	0.94	0.028	0.86	0.95
“Turn Right”	10	**0.92**	0.94	0.060	0.75	0.95
“Turn Left”	9	0.94	0.94	0.003	0.94	0.95
“Left Spin”	11	0.93	0.95	0.036	**0.83**	0.95
“Right Spin”	10	**0.95**	0.95	0.005	0.93	0.95
“Stop”	14	0.94	0.94	0.010	0.92	0.95

Table 34: Descriptive Statistics for the trust level of speech recognition.

The sequence “Stop” is more familiar and could be said by 14 users. The sequence “Right Spin” has the highest average of recognition and the “Turn Right” has the lowest average. The number of not recognized sentences was also registered for each user and the mean value was approximately of 4 errors while the median was just 1 error.

The users’ ability to use the joystick and head movements was also analysed. Table 35 shows how many users could perform the movement to achieve the green dot.

	Joystick			Head Movements		
Ability	**Task 1**	**Task 2**	**Task 3**	**Task 1**	**Task 2**	**Task 3**
No	13	13	13	6	12	8
Yes	21	21	21	28	22	26

Table 35: Ability in performing joystick and head movements.

Some examples of the trace of the movement can be observed in the next figures (Figure 91 and Figure 92).

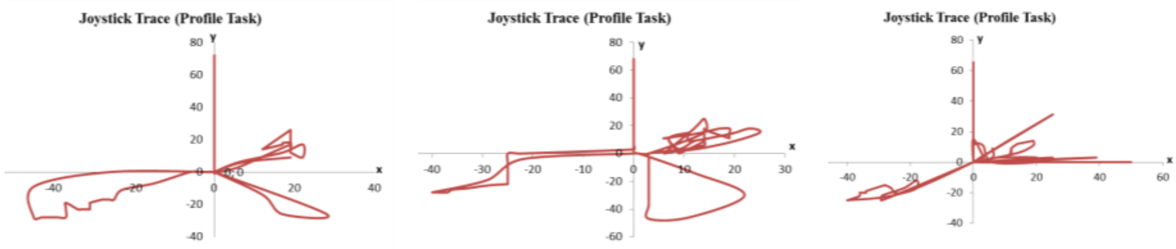


Figure 91: Examples of joystick trace in a profile task.

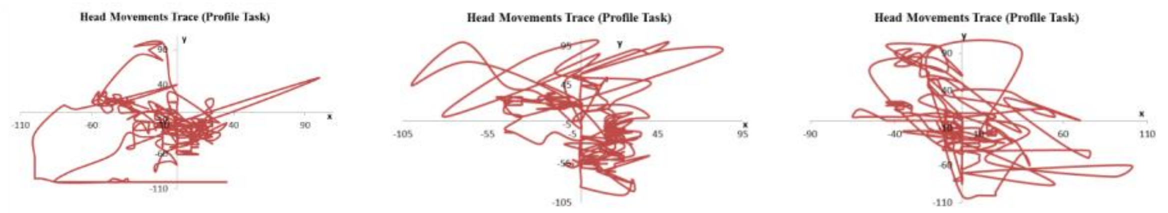


Figure 92: Examples of head movements trace in a profile task.

The ability to execute the facial expressions was also analysed (Figure 93). Table 36 shows the number of users that could perform the facial expressions analysed. The capacity to perform the facial expressions was evaluated by the therapist.

	Facial Expressions								
Ability	**Blink**	**Furrow**	**Left blink**	**Right blink**	**Clench**	**Eye-brows**	**Left smile**	**Right Smile**	**Smile**
No	15	28	33	32	15	21	34	34	14
Yes	19	6	1	2	19	13	0	0	20

Table 36: Ability in performing the facial expressions.

The results presented in Table 36 reflect the difficulty of the cerebral palsy patients have in controlling the facial expressions. For instance, the left and right smiles could not be performed by any member of the sample.

Figure 93: Examples of profiling tasks.

These preliminary results show the difference between users and the importance of having an adapted interface for each user that considers his abilities in using the different modalities for driving the intelligent wheelchair.

After this profiling phase, it was possible for the specialists to inform the patients which were the more suitable input devices that they could use to drive the IW. In fact, the profile avoids the frustration of trying to drive the wheelchair without being able to do it with a specific input device. Section 5.1.5 describes the experiments and results of the users when using the *IntellSim* to drive the IW. These experiments confirm the users' ability to drive the IW when the appropriate input devices are selected.

Table 37 shows the distribution of the number of patients that were able to drive the intelligent wheelchair using the different input devices: Joystick; Microphone for voice commands; Wiimote for the head movements. This ability was decided by the therapists that supervised the experiments aided by the results achieved by the patients in the user profiling. The criteria used was that if the users were completely unable to perform any of the tests of the user profiling using a given input device they were considered as unable to use that input device.

Input Device	Frequency
Joystick	1
Microphone	1
Wiimote	13
Wiimote and Joystick	12
Wiimote, Joystick and Microphone	7

Table 37: Input devices distribution for driving the intelligent wheelchair.

The profile data was also used to verify the relation between the fulfilment of the tasks and the used input device. Driving the intelligent wheelchair with the buttons of the joystick was a very demanding task for this group of users, since fine movements and high agility are necessary to perform the buttons selection. The analysed variables were the average number of successes in performing the tasks with head movements and with the joystick and the percentage of recognition of the voice commands, the total number of voice recognition errors and average of voice recognition of all the voice commands. Facial expressions were not considered to drive the intelligent wheelchair, since it was a tiring and frustrating task to be carried out by patients. Hence, the average number of successes in performing the tasks using facial expressions was not considered.

In order to verify the relation between the input variables (as described above) and the input device(s) used to drive the IW a decision tree was applied. The choice of this classification method at this stage is justified by the need to better understand the variables screening and because decision trees are very intuitive and it is easy to understand the results [9].

The algorithm to induce the decision tree was the one available in the Rapidminer software. Basically, the decision tree learner works similarly to Quinlan's C4.5 or CART [172] [236]. Whenever a new node is created at a certain stage, an attribute is picked to maximise the discriminative power of that node with respect to the examples assigned to the particular sub-tree. This discriminative power is measured by a criterion that in this case was the accuracy. The tree was pruned which means that leaves that do not add to the discriminative power of the whole tree were removed. Figure 94 shows the model obtained by inducing a decision tree.

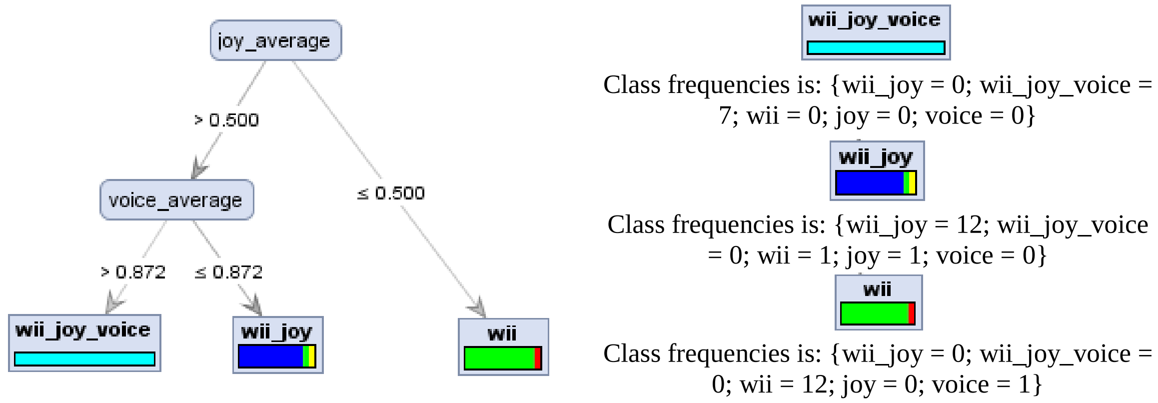


Figure 94: Decision tree for the relation between the variables and the input device.

The results reflect that most of the patients were able to perform the tasks with the head movements (input device wiimote): the average number of successes using the head movements was 33% for this modality to be advised. The nodes of the decision tree are composed with the average number of success in performing the tasks with the joystick and the percentage of recognition of the voice commands. For example if the average number of success in performing the tasks with the joystick was higher than 50% then the joystick was advised. The average of voice recognition of all the voice commands should be higher than 87%.

These results led to the idea of composing a command language adapted to each user. This command language should be automatically derived from the analysis of the task performance using the profiling. In fact, the developed model for user profiling provided a stable protocol to induce knowledge about the users' abilities.

Users Suffering from Cerebral Palsy using BCI

Another line of experiments, using the Brain Computer Interface, was the application of the raw data from its 14 sensors and the values of its accelerometer acquired using the profile module for facial expression and thoughts classification. The objective was to understand how feasible it was classifying facial expressions and thoughts, using the BCI, for driving the IW. The experiments were divided into two parts: facial expressions and thoughts [7]. Only the data of the correct facial expressions and thoughts were used. This was possible because of the component in the manager that allows indicating which facial expressions are being correctly performed. For each experiment the classification was performed pre-processing the data and without any type of pre-processing. The algorithms applied in this test were: Naïve Bayes; Support Vector Machines, Neural Networks, Nearest Neighbour and Linear Discriminant Analysis. The evaluation was made using the 10-fold cross validation. Signal pre-processing was based on Hjorth parameters and a forward approach for variable selection. Table 38 presents the results achieved without and with optimized selection of variables.

Accuracy of models without [with] optimized selection of variables			
Algorithms	**Acc (%) Expressions**	**Acc (%) Thoughts**	**Parameters**
Naïve Bayes	36.36 [54.64]	15.79 [23.22]	Laplace correction
Support Vector Machines	28.73 [43.55]	15.70 [26.96]	kernel type=radial basis function; epsilon=0.001
Neural Networks	35.27 [**55.36**]	18.39 [**27.57**]	training cycles=500; learning rate = 0.3; momentum=0.2
k-Nearest Neighbour	17.64 [55]	8.68 [25.56]	k=4; mixed measure=mixed euclidean distance
Linear Discriminant Analysis	25.91 [54]	23.19 [25.94]	---

Table 38: Accuracy and parameters for facial expressions and thoughts without and with selection of variables.

The results are significantly better with an optimized selection of variables, where an application of neural networks can achieve 55% of accuracy. The accuracy of thoughts classification also increases with the variable selection, although even the increased values are considerably low. The best accuracy was achieved using a neural network and it was possible to verify a substantial improvement on the facial expressions and thoughts recognition using the variable selection process previously explained.

Finally, tests (ten trials for each case) showed that it was possible to complete the circuit previously shown in Section 5.1.2.1 and Figure 77, using the *IntellSim*, with only facial expressions and thoughts as the wheelchair inputs. The mean time for completing the circuit using other kinds of input methods was 1’53’’ (with a standard deviation of 1.4 seconds). With facial expressions the average time was 5’42’’ with a standard deviation of 9.2 seconds. Finally, using thoughts as the wheelchair input method, the average time necessary was 12’13’’ with 17.7 seconds of standard deviation. Although it was possible to complete the circuit using only thoughts, this input method is still far from being comfortable to enable driving in a robust manner, an intelligent wheelchair. However, there are patients that are completely unable to use any other kind of method such as joystick, head movements or voice for driving the wheelchair in a robust manner. Thus, this method, although not comfortable, may still be very useful in creating a robust flexible IW multimodal interface.

5.1.4.3 Conclusions

The user profiling module was tested in several phases in order to improve the sequence of the tests used for gathering this profile. Several conclusions could be taken from data gathered using the user profiling. First, the lack of ability in using the buttons of the joystick by the cerebral palsy users was noticeable. Also, it was possible to conclude that the time of three seconds required in the experiments, for the red dot to be in front of the green dot, in order to consider the task as completed, was too long and unnecessary. In fact, although patients could perform the movements with the head and with the joystick requiring that time was an extra difficulty for these tests.

The success variables are of great importance and the profile gives a stable protocol for testing the abilities of the users. Another interesting conclusion that could arise from these experiments was that users showed some abilities that were completely unexpected by the occupational therapists who cared for the patients. This reveals the importance of testing the ability of the users before testing the IW.

5.1.5 IntellSim Experiments

The experiments with the *IntellSim* were performed with patients suffering from cerebral palsy and after the profiling session. To better understand the next results the sample characterization will be presented. Besides that, it is also important to reinforce that cerebral palsy is defined as a group of permanent disorders in the development of movement and posture [348]. It causes limitations at the level of daily activities because of a non-progressive disturbance which occurs in the brain during the fetal and infant development [349]. The motor disorders in cerebral palsy are associated with deficits of perception, cognition, communication and behaviour. In general, there are also episodes of epilepsy and secondary musculoskeletal problems [349].

5.1.5.1 Samples Characterization

Adults Suffering from Cerebral Palsy

The individuals included in this study suffer from cerebral palsy and were classified in the levels IV (21%) and V (79%) of the Gross Motor Function Measure. These are the highest levels in the cerebral palsy severity degree. The sample size was composed of the 34 individuals and all require the use of a wheelchair. The mean of age was 28 years old with 71% males and 29% females. In terms of school level 15% did not answer, 8% are illiterate, 12% just have the elementary school, 29% have the middle school, 27% have the high school and only 8% have a BSc. The dominant hand was divided as: 50% for left, 32% for right hand and 18% did not answer. Another question was the frequency of use of information and communication technologies: 33% did not answer; 38% answered rarely; 21% sometimes; 6% lots of times and 3% always. The aspects related to experience of using manual and electric wheelchair were also questioned. Table 39 shows the distribution of answers about autonomy and independency using the wheelchair and constraints presented by these individuals.

Experience, Autonomy, Independence and Constraints					
Variables		**n**	**Variables**		**n**
Use manual wheelchair			Cognitive constraints		
	no	21		no	14
	yes	13		yes	17
Use electric wheelchair			Motor constraints		
	no	9		no	0
	yes	25		yes	34
Autonomy using wheelchair			Visual constraints		
	no	8		no	18
	yes	26		yes	15
Independence using wheelchair			Auditive constraints		
	no	8		no	34
	yes	26		yes	0

Table 39: Experience using wheelchair, autonomy, independence and constraints of the cerebral palsy users.

Children Suffering from Cerebral Palsy

In Portugal, and in many other countries, it is not common for children to have a wheelchair at a young age. The investment of this assistive technology is done later in life. However, using the simulator, it was possible to verify the potential usefulness of providing an intelligent wheelchair to young children. The methodology was adapted to a case study. Another sample composed of six children (four boys and two girls) participated in the case study, three five years old and three twelve years old. Three children were classified with the level of the GMFCS IV and the other three with level V.

5.1.5.2 Circuit and Tasks

Adults' Circuit and Tasks

Using *IntellSim* several experiments were performed changing the conditions of the environment. A map was created integrating paths with several degrees of difficulty (Figure 95 and Figure 96). The overall circuit passes through two floors and the link between floors is a ramp. The map was divided into three parts. The first part is characterized by having simple and large corridors without any kind of obstacles except pillars. The second part has narrow corridors, ramps and obstacles. The last part involved a circuit entering in three rooms with different kind of illumination and noise.

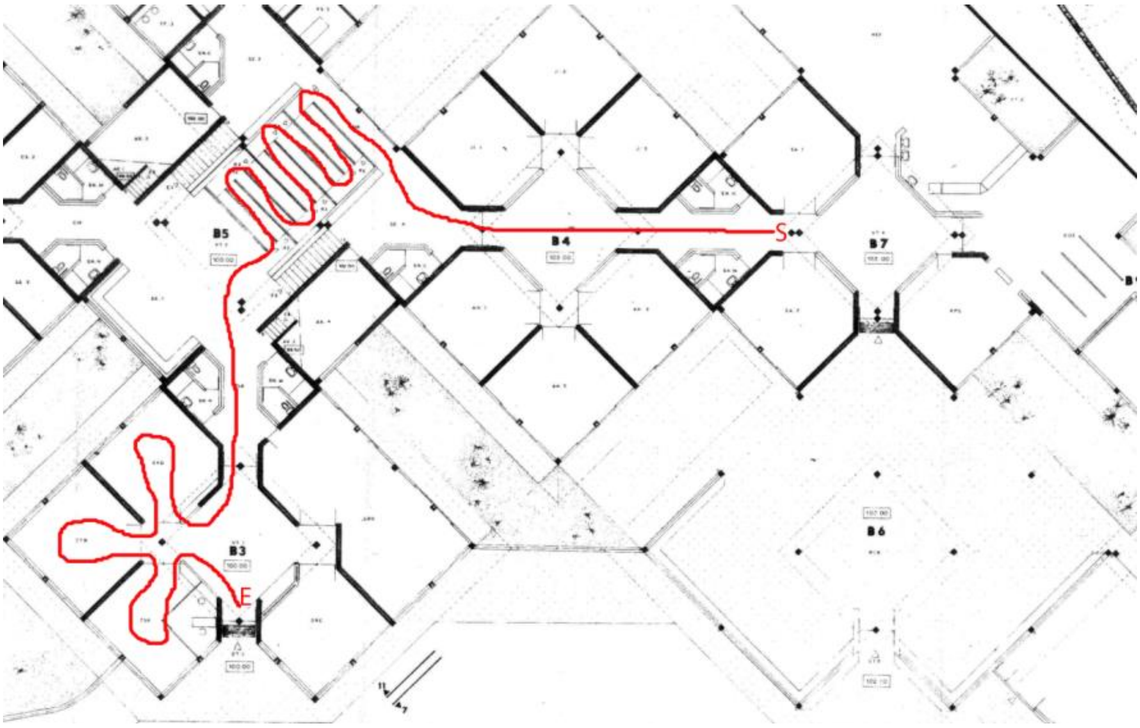


Figure 95: Overall circuit for the intelligent wheelchair experiments.

In the environment there were 15 blue balls that should be collected (by passing near them) and a yellow star that corresponds to the end of the circuit. For each collected object a point was awarded to the user in the serious game score.

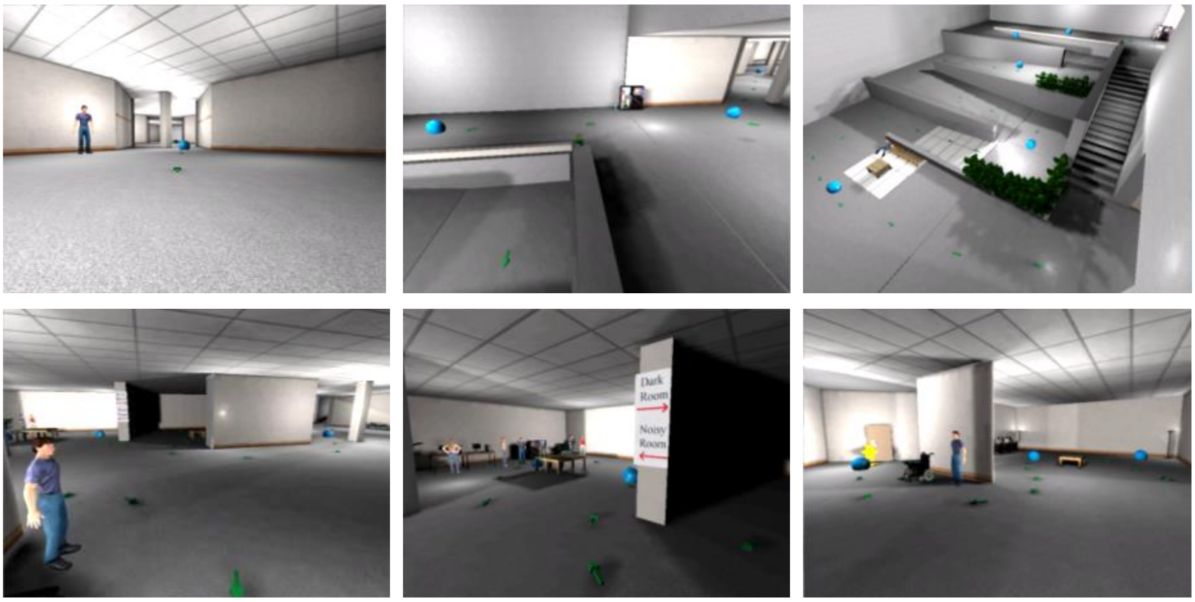


Figure 96: Images from the IntellSim circuit.

Children's Circuit and Tasks

The scenario for children was divided into five spaces (Figure 97) and five levels of difficulty, from the easiest to the more difficult, were considered. This serious game had some rules that are explained next: in the environment there are objects such as blue balls that need to be collected and a yellow star that correspond to the end of the level. Each object collected corresponds to one point. There are in the environment static objects like pillars, tables, wheelchairs and dynamic such as people. The objective was to achieve the highest difficulty level, with the minimum of trials and collisions and the highest score possible.

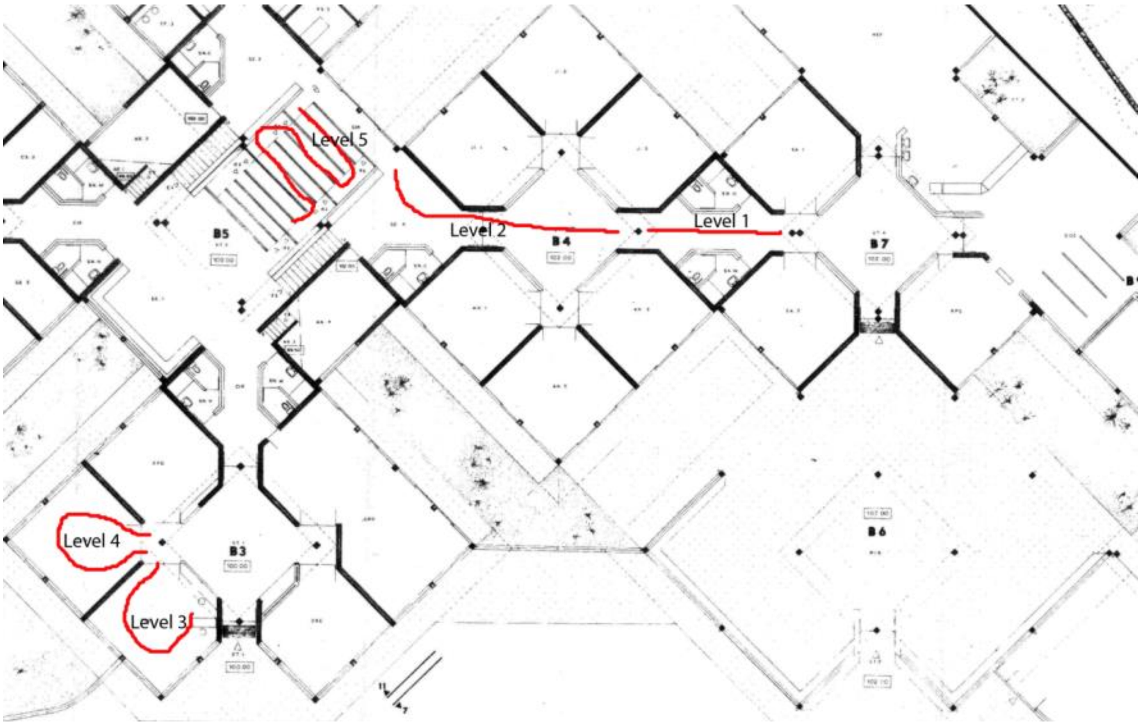


Figure 97: Map with the levels created for the tests with children.

Figure 98 shows an image of all the five levels. In the first level the objective was to go straightforward and collect a yellow star. In the second level the children should first go forward, then pass through a narrow space (between the wall and a pillar), then turn and collect a blue ball and the star. The track at level three is characterized by having the necessity of entering in a room, going around a table in the middle, and collecting two blue balls along the way and a star in the final. Level four is similar to level three, however with more dynamic and static objects that increase the difficulty of manoeuvring the wheelchair. The last level consists in driving the wheelchair along a ramp with three lances. In this level they should collect three blue balls and a star avoiding a dynamic object.

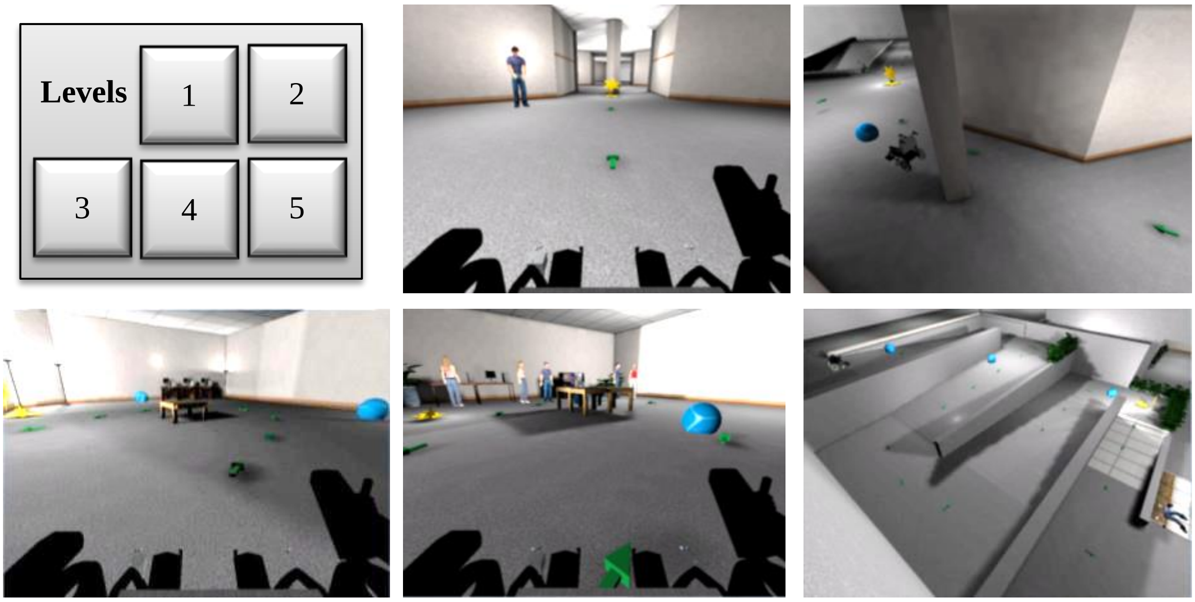


Figure 98: Levels created for the tests with children.

The evolution in terms of difficulty progress should be from the basic capabilities to the more complex as it is defended by Cook and Hussey [350]. In each level the user has three attempts to perform the desired task in order to facilitate the performance, the learning process and the opportunity of success. Eight minutes was the limit time imposed for each level and five the maximum number of collisions. One other reason for creating this serious game, in order to test children driving the wheelchair, is the fact that playing is their main occupation area and also the more influent one in their development. With this game, it is given an opportunity for exploration and participation to children (and adults) with cerebral palsy.

After the experiments performed using the *IntellSim* the users had the opportunity to give their opinions using the questionnaire previously described (Annex D) in Section 4.5.3.1.

5.1.5.3 Results

Adults' Results

The results about the opinion of the users and their performance are organized in Table 40. Many of the patients could not express their opinions perfectly (for example in the cases of cognitive constraints or lack of ability in expressing themselves), for that reason the number (n) of users that could manage to give their opinions are also present in Table 40. Another important aspect that must be pointed out is the number of users that made the experiments with a particular input device.

	IntellSim experiments with patients suffering from cerebral palsy					
	n	**Mean**	**Median**	**Std**	**Min**	**Max**
Usability and Safety						
Score SUS	21	67.0	67.5	12.5	50	95
Safety managing IW	21	--	Agree	--	Dis	SAgree
Control of the IW	21	--	Agree	--	SDis	SAgree
Easy to drive the IW in tight places	21	--	Ind	--	Dis	SAgree
The IW do not need to much attention	21	--	Dis	--	SDis	Agree
Satisfaction level						
Joystick manual mode	12	--	VSatis	--	Ind	VSatis
Voice commands	7	--	Satis	--	Diss	VSatis
Head movements	20	--	Satis	--	Ind	VSatis
Tired						
Joystick manual mode	12	--	Dis	--	SDis	Dis
Voice commands	7	--	SDis	--	SDis	Agree
Head movements	20	--	Dis	--	SDis	Agree
Frustrated						
Joystick manual mode	12	--	Dis	--	SDis	Ind
Voice commands	7	--	SDis	--	SDis	Ind
Head movements	20	--	SDis	--	SDis	Agree
Performance						
Time (min)						
Joystick manual mode	19	12.6	9.5	8.6	5.6	42.4
Voice commands	7	21.1	26.1	10.8	7.6	36.3
Head movements	31	17.2	16.6	7	7.2	36.9
N of collisions						
Joystick manual mode	19	9	6	12.8	0	58
Voice commands	7	12	12	7	2	23
Head movements	31	8	6	6	0	23
Number of objects collected						
Joystick manual mode	19	12.7	14	3.6	4	15
Voice commands	7	11.7	15	5.4	2	15
Head movements	31	13.8	15	2.7	3	15

Legend: Stimes – sometimes; SDis – strongly disagree; Dis – disagree; Ind – indifferent; SAgree – strongly agree; VDiss – very dissatisfied; Diss – dissatisfied; Satis – satisfied; VSatis – very satisfied

Table 40: Results of the experiments in IntellSim.

The degree of difficulty and preference using the joystick, voice and head movements can be observed in Figure 99.

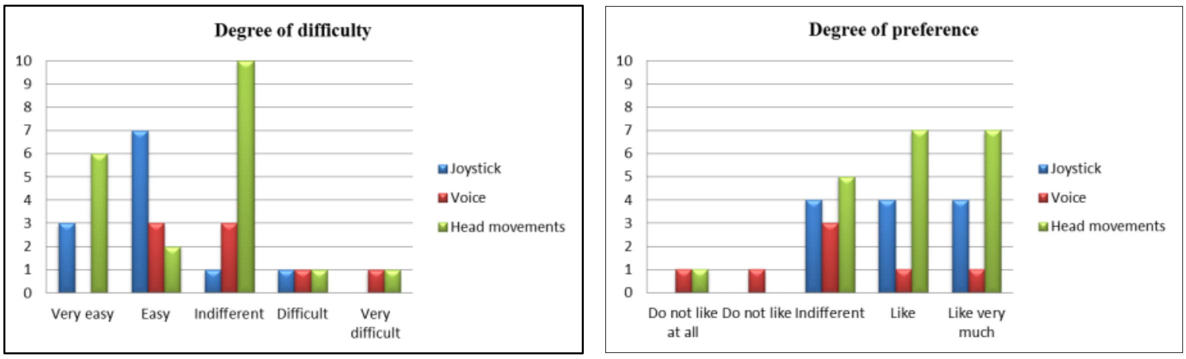


Figure 99: Degree of difficulty and preference using joystick, voice and head movements.

The data from the logs allows plotting the circuits after the experiment. It is a way of analysing the behaviour of the users using different commands. Table 41 shows examples of the circuits performed by three patients that could perform the experiments with joystick, voice and head movements. The first line of images correspond to joystick circuits, the second line to voice commands and the third line to the circuits executed using head movements.

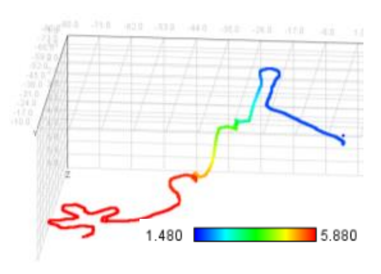
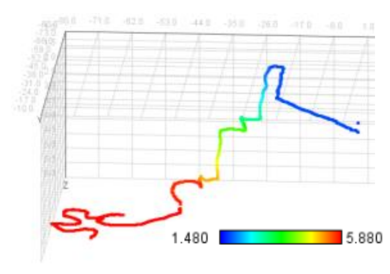
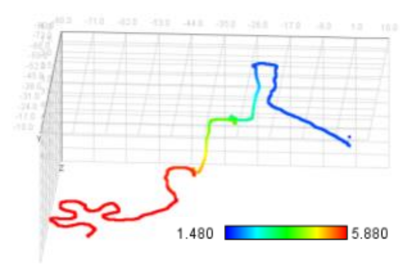
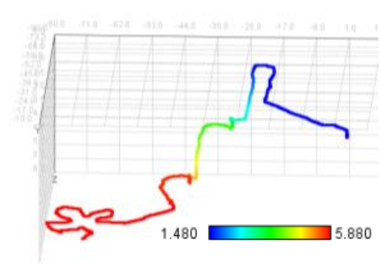
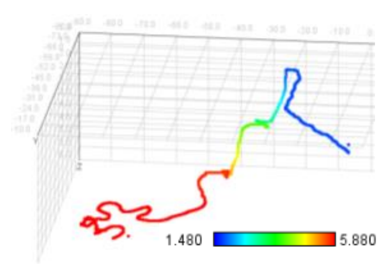
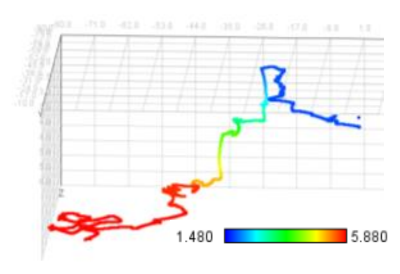
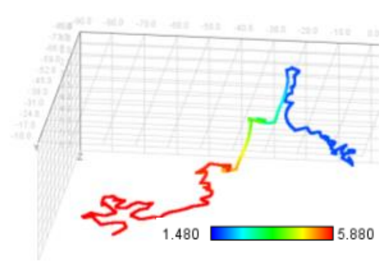
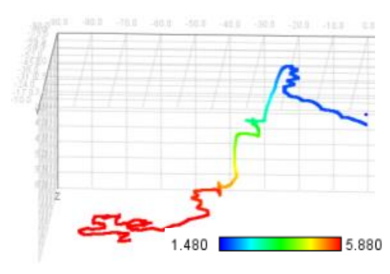
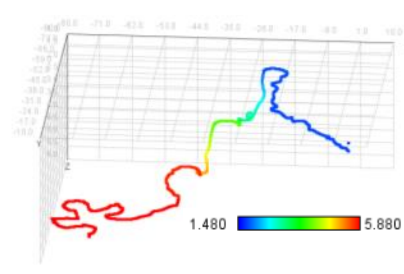
Individual A	Individual B	Individual C
		
		
		

Table 41: Circuits performed by patients suffering from cerebral palsy with joystick (1st line), voice (2nd line) and head movements (3rd line).

It is interesting to notice that the path is smoother in the case of the joystick. These three individuals (A, B and C) are autonomous and independent in driving their own electric wheelchairs with joystick (Level IV of the Gross Motor Function). The results also demonstrate that it is possible to drive the IW with head movements and voice. Table 42 shows examples of the path of individuals that could only perform the circuit with head movements and in this case the ability is very good.

This analysis allows reinforcing the idea of using a multimodal and adapted interface to the users for driving the intelligent wheelchair.

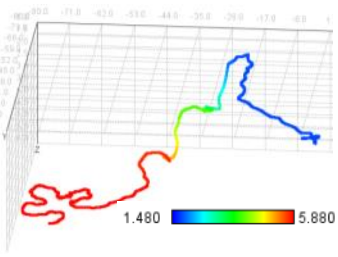
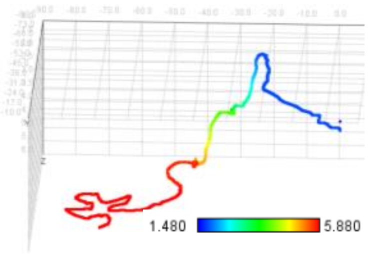
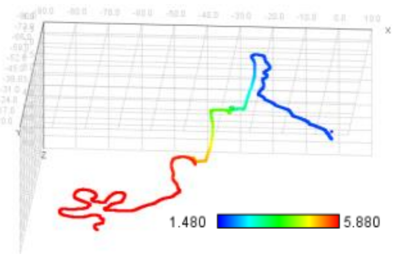
Individual D	Individual E	Individual F
		

Table 42: Circuits performed by patients suffering from cerebral palsy with head movements.

Children's Results

The six children performance was individually analysed. All the children tested the profiling and the *IntellSim* experiments were performed using the input devices that could be correctly used by each of them. The BCI was not used since its size is not adequate for the children's head. Given their abilities, as explained before, each child used only the input devices that were able to control. Thus, children A, B and C performed the tests with the joystick and head movements; while children D and E performed only with joystick and child F only with the head movements. Table 43 shows the global results after the first trial of the five levels.

Children Experiments Results								
	Joystick Experiments				Head Movements Experiments			
Child	**Total Time**	**Total Collisions**	**Objects Collected**	**Maximum Level**	**Total Time**	**Total Collisions**	**Objects Collected**	**Maximum Level**
A	13.17	5	13	5	11.74	0	13	5
B	15.31	5	13	5	9.69	6	2	2
C	6.33	0	13	5	6.71	5	13	5
D	36.69	19	13	5	--	--	--	--
E	12.9	6	3	2	--	--	--	--
F	--	--	--	--	5.86	5	3	2

Table 43: Children's performance results after the first trial.

Child A presents the best performance with the head movements taking 11.74 minutes to complete all five levels without any collision. Comparing the performance with the joystick, the child A presented some difficulties with the "stopping" task and therefore collided five times. However the child could manage to finish every level collecting all the objects with both modalities.

Child B collected all the objects driving the IW with joystick with only five collisions. The performance with head movements was worse than with the joystick. The second level was the higher level that the child could achieve, referring that he had some difficulties and was tired after that. He could collect two objects of the three available in the two levels and needed 9.69 minutes to do it.

The only child with previous experience in driving autonomously an electric wheelchair with a joystick was child C. The performance was very good with the joystick and he obtained the higher score with the lowest time of all the children that tried the joystick. The performance with the head movements was also good in terms of time, however with a total of five collisions.

Child D presented some difficulties in terms of adaptation to the system and repeated the first level three times until the time limit was exceeded (9.68 minutes and 8.03 minutes for the first and second attempts respectively). In the third attempt the child could achieve the objective spending only 3.13 minutes without any collision. At level four there were two tries because the child had six collisions in the first try. The joystick was the only input device used by this child. The evolution in terms of performance was high considering the diagnostic of dystonic tetra-paresis and consequent abrupt changes of tone in global patterns of movement.

Child E only used the joystick and the performance was very bad because of the child behaviour. The participation was not the more enlightening, since the focus of the child was playing instead of pursuing the objective of the experiments. Although the child demonstrated capacities in using the head movements, the child refused to do it. A second day was scheduled, however unmarked by the parents.

The last child was the most severe case classified by the GMFCS and the head movements was the only option used to perform the experiments since it was the only input device this child could minimally control. The results were not very good because the level of head control was very poor. The child demonstrated some cognitive constraints and anxiety leading to the end of the tests after the second level. The time spent was 5.86 minutes after the two levels and collected all the objects colliding five times.

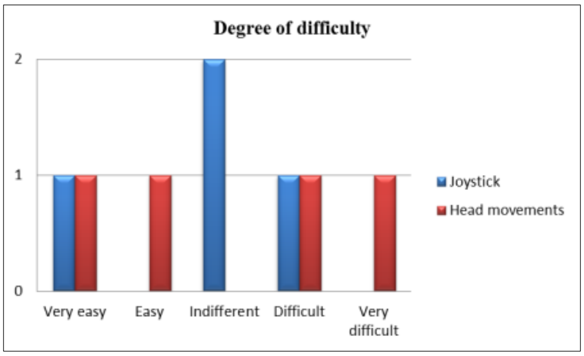
The children’s opinion about the experiments was also registered (Table 44). The responses were given only by five of the six children. The joystick users were satisfied with the experiment. Three were satisfied and the child B was very satisfied. One child that used the head movements to drive the IW was very satisfied, however two answered not satisfied with the experience (the fact that the wiimote is integrated in a hat was a constraint since the children did not normally like to use it).

	IntellSim experiments with children suffering from cerebral palsy					
	n	Mean	Median	Std	Min	Max
Usability and Safety						
Score SUS	5	51	50	6.8	42.5	60
Safety managing IW	5	--	Agree	--	Agree	SAgree
Control of the IW	5	--	Agree	--	Dis	Agree
Easy to drive the IW in tight places	5	--	Agree	--	Ind	Agree
The IW do not need to much attention	5	--	Agree	--	SDis	SAgree
Satisfaction level						
Joystick manual mode	4	--	Satis	--	Satis	VSatis
Head movements	4	--	Diss	--	VDiss	VSatis
Tired						
Joystick manual mode	4	--	Ind	--	Dis	SAgree
Head movements	4	--	Ind	--	SDis	SAgree
Frustrated						
Joystick manual mode	4	--	Dis	--	SDis	SAgree
Head movements	4	--	Ind	--	SDis	SAgree

Legend: Stimes – sometimes; SDis – strongly disagree; Dis – disagree; Ind – indifferent; SAgree – strongly agree; VDiss – very dissatisfied; Diss – dissatisfied; Satis – satisfied; VSatis – very satisfied

Table 44: Children's opinions results.

In order to better understand the differences between the opinions in terms of difficulty and preference using the joystick and the head movements a frequency analysis was conducted. Figure 100 shows the distribution of the children's answers in terms of degree of difficulty and preference.



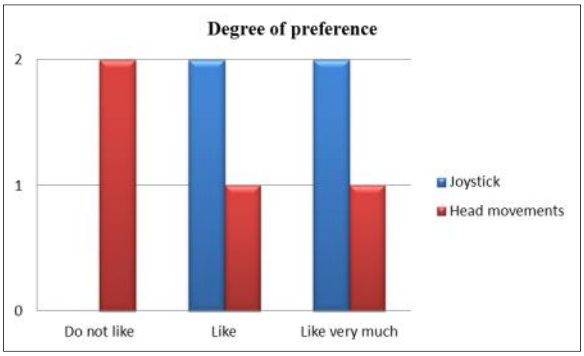


Figure 100: Children's degree of difficulty and preference with joystick and head movements.

The tendency in terms of the degree of satisfaction, preference and frustration could be accessed. The degree of difficulty by using the head movements has a more disperse distribution than with joystick and in terms of preference two children said that they did not like using the head movements although all the answers were like and like very much when using the joystick.

Figure 101 shows some of the circuit paths traversed by the children in all the five levels of the game. Children A and C could realize all the levels of the game.

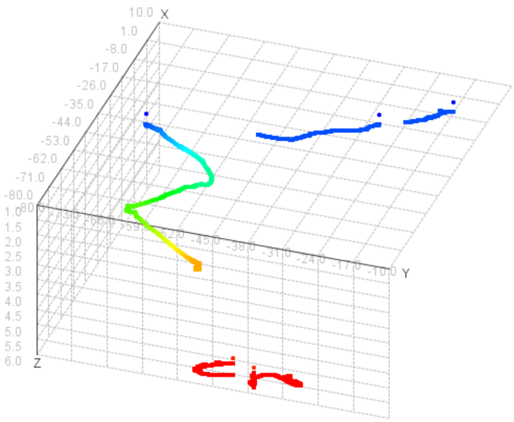
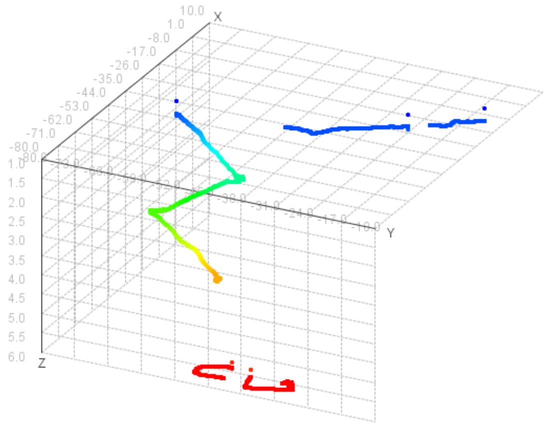
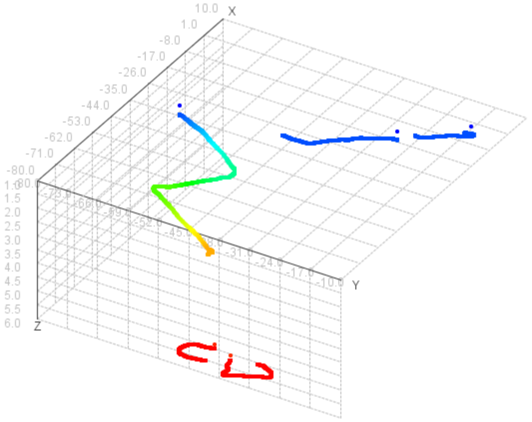
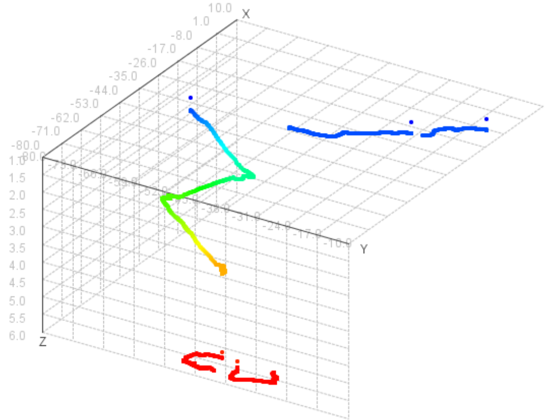
Child A	**Child C**
 with joystick	 with joystick
 with head movements	 with head movements

Figure 101: Examples of the tracks performed by two children using joystick and head movements.

A more detailed representation of the path is revealed in Figure 102. Child A could collect all the objects in level three using the joystick, however the route was not the shortest.

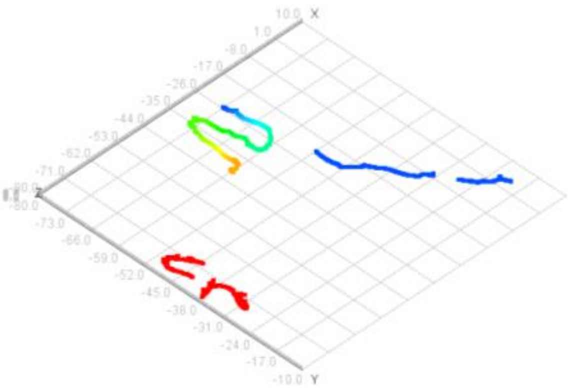
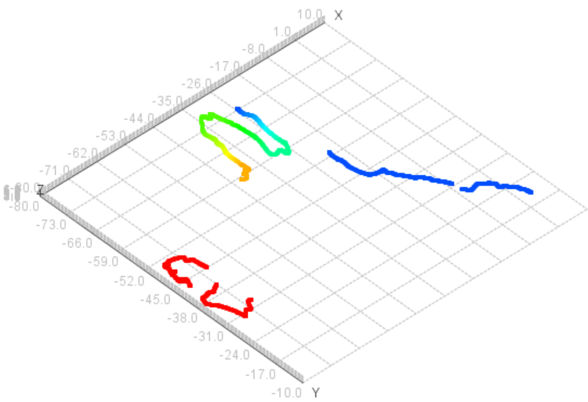
Child A with joystick	**Child C** with head movements
	

Figure 102: 2D examples of the tracks performed by two children.

With this representation it is possible to quickly observe the tracks followed by the users also revealing the importance of the data acquired from the simulator.

5.1.5.4 Conclusions

The average usability score was satisfactory in the groups of individuals that are potential users of IW. In the case of the children the average usability was lower than with the adults. However, the sample size, the difficulty in using the input devices that are not adapted for young children and the lack of experience using wheelchairs were the main reasons for this lower value. Nevertheless, the profile module and the simulator are important tools to occupational therapists to observe and verify the acquired competences of adults along with young children.

Another important conclusion was the relation between the ability in performing the tasks in the profile module and the ability in using a certain input device for driving the intelligent wheelchair. All the users that could perform a particular set of tasks in the profiling using an input device could also drive the intelligent wheelchair with the same input device.

These experiments allowed to take several conclusions and to use them to perform changes in the simulator, manual, shared and automatic controls, and tasks for the profiler module. This was the base to finish the Data Analysis System and plan the experiments to fully test this final system.

5.2 Data Analysis System Experiments and Results

After the initial tests it was important to perform experiments to verify the adaptation of the interface to the real patients. The profiling tasks (automatic profile extraction methodology) were set in order to accomplish the objectives of the multimodal input device and control advisors and the command language.

5.2.1 Sample Characterization

The sample was composed of 11 patients with cerebral palsy with the level IV (27.3%) and V (72.7%) of the Gross Motor Function Measure.

The mean of age was 27 years old with 64% males and 36% females. In terms of school level, 1 is illiterate, 1 has completed elementary school, 4 have completed middle school, 3 have completed high school and 2 have a BSc. The dominant hand was divided as: 82% for left, 18% for right hand. The frequency of use of information and communication technologies was also characterized: 7 answered rarely; 2 sometimes; 1 lot of times and 1 always. The aspects related to experience of using manual and electric wheelchair were also questioned. Table 45 shows the distribution of answers about autonomy and independency using the wheelchair and constraints presented by these individuals.

Experience, Autonomy, Independence and Constraints					
Variables		**n**	**Variables**		**n**
Use manual wheelchair			Cognitive constraints		
	no	10		no	8
	yes	1		yes	3
Use electric wheelchair			Motor constraints		
	no	1		no	0
	yes	10		yes	11
Autonomy using wheelchair			Visual constraints		
	no	1		no	3
	yes	10		yes	8
Independence using wheelchair			Auditive constraints		
	no	1		no	11
	yes	10		yes	0

Table 45: Experience using wheelchair, autonomy, independence and constraints of the cerebral palsy users.

5.2.2 User Profiling for the IDAS

The motivation for generating an IW command language, adapted to each user, was to use the automatic profile extraction methodology, previously explained, in order to really be able to give the best way, for each user, to robustly and safely command its intelligent wheelchair.

The voice inputs were organized in order to give several choices for the command language. The input options in this case were: “Go”, “Front”, “Forward”, “Back”, “Right”, “Left”, “Turn”, “Spin” and “Stop”.

The five positions of the Joystick and the Head Movements were set accordingly to the usual necessary positions for driving a wheelchair “East”, “North”, “South”, “West” and “South-west” (Figure 103).

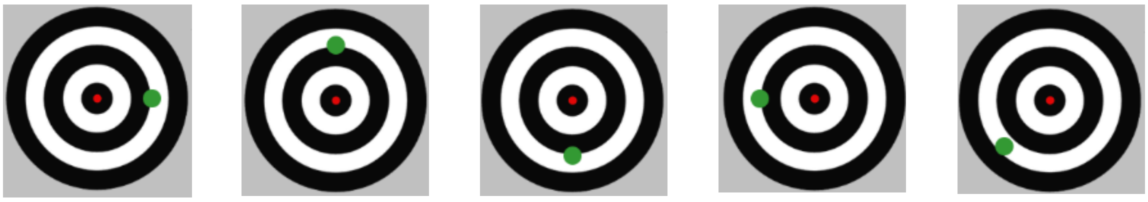


Figure 103: Positions of the joystick and head movements in the profiling.

Figure 104 shows examples of the joystick and wiimote tracking using the profile module.

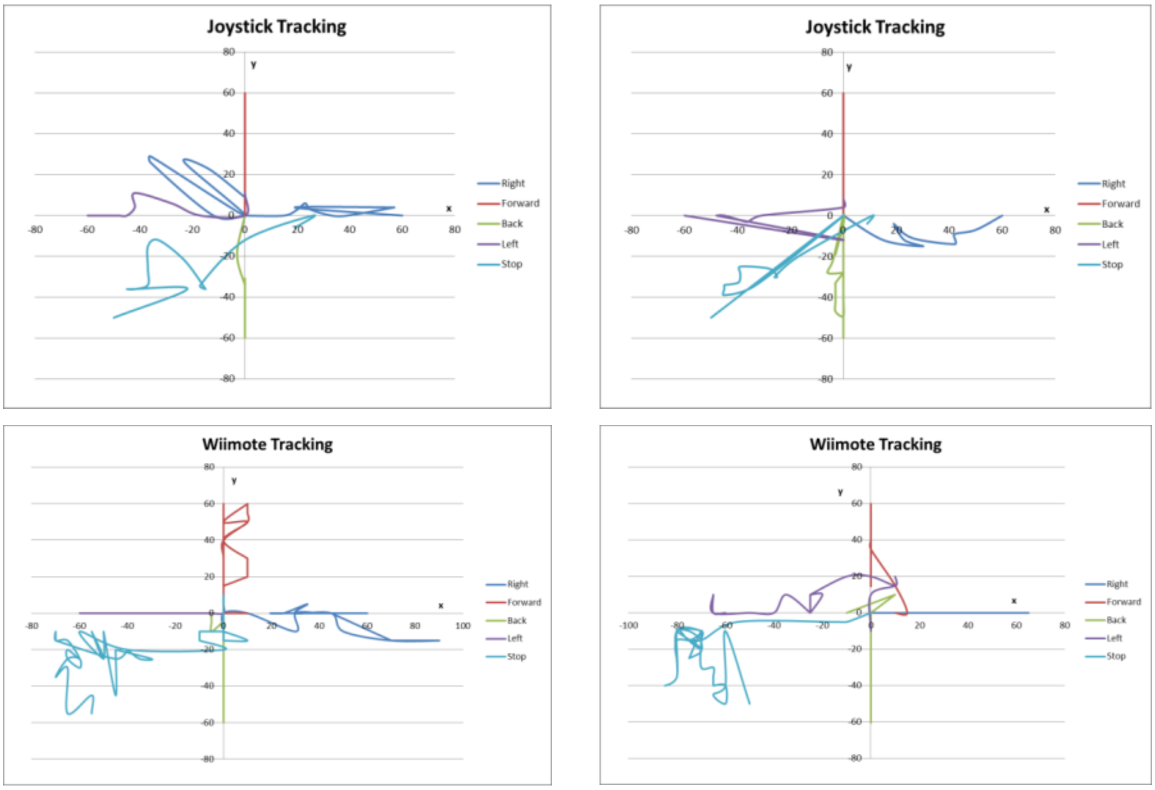


Figure 104: Joystick and wiimote tracking using the profile module.

An extension of the profiling was also created in order to record all the information available, such as facial expressions, thoughts and buttons pressed at the joystick.

After the profiling, the occupational therapists were asked three types of information: which input device is advised, which control best suits the patient and what command language is advised.

5.2.3 Input Device Advisor

In order to validate the Input Device Advisor, the results/conclusions achieved by this system were compared with the conclusions achieved by the combined opinion of two therapists. This therapist's combined opinion was achieved by analyzing the user capabilities and its performance in the user profiling and briefly discussing the issue among them to achieve a final conclusion.

The experiments related in this section compare the input device that was advised by the specialists and the input device selected by the input device advisor (described in Section 4.7.3). Table 46 shows the results for input devices advised by the occupational therapist and by the IDAS with the respective accuracy. In Table 46 "x" defines an input that the user is capable of using and "--" represents an input that the user is unable to use. The accuracy is given by the F-Measure of the confusion matrices.

Patient		Input Device [accuracy]		
	Buttons	Joystick	Wiimote	Microphone
P1				
Specialist	--	x	x	--
IDAS	--	x [1]	x [1]	-- [0.27]
P2				
Specialist	--	x	x	--
IDAS	--	x [0.96]	x [1]	-- [0.14]
P3				
Specialist	--	x	x	--
IDAS	--	x [0.68]	x [1]	x [0.32]
P4				
Specialist	--	x	x	x
IDAS	--	x [1]	x [1]	x [0.49]
P5				
Specialist	--	x	x	x
IDAS	--	x [0.88]	x [1]	x [0.40]
P6				
Specialist	--	x	x	--
IDAS	--	x [0.80]	x [1]	-- [0.12]
P7				
Specialist	--	x	x	x
IDAS	--	x [1]	x [1]	x [0.48]
P8				
Specialist	--	x	x	--
IDAS	--	x [0.68]	x [1]	-- [0.11]
P9				
Specialist	--	x	x	x
IDAS	--	x [1]	x [1]	x [0.30]
P10				
Specialist	--	x	x	x
IDAS	--	x [0.96]	x [1]	x [0.53]
P11				
Specialist	--	x	x	--
IDAS	--	x [0.60]	x [1]	-- [0]

Table 46: Input device advisor results.

Analysing the input devices advised by the IDAS and comparing it with the input device advised by the specialist, after the profiling, all the cases agreed except in one case: patient three (P3) had three options including the microphone however the specialist did not advised this device. Analysing the overall accuracy for the microphone, in fact the value was 32%, it is very difficult for a human to have a complete perception of the performance.

Another advantage of the IDAS is that it provides a recommended order for using the input devices taking into account the accuracy value. The first option should be the device with the highest accuracy value while the last option should be the device with the smallest accuracy value.

5.2.4 Wheelchair Control Advisor

The shared control can be used for helping patients with severe handicaps while they drive the wheelchair as demonstrated in previous experiments (Section 5.1.3). Both the limits of the accuracy and the advised wheelchair control were described in Section 4.7.4. If the accuracy has a value between 0 and 30% then the aid control used is at a level of 100%; if the accuracy value is between 30% and 70% then the aid control used is at 50% and if the accuracy is higher than 70% then only obstacle avoidance is advised using the manual control since the user is able to control the IW. These control advisor limits were applied both to the cases with joystick and wiimote for head movements.

Table 47 shows the IDAS results in terms of the best wheelchair control aid level for each user. In Table 47 "x" defines a wheelchair control advised and "--" represents a wheelchair control that the user is unable to control. The accuracy is given by the F-Measure of the confusion matrices.

	Shared Control [accuracy]					
	Joystick			Wiimote		
Patient	**Aid 100%**	**Aid 50%**	**Obstacle Avoidance**	**Aid 100%**	**Aid 50%**	**Obstacle Avoidance**
P1	--	--	x	--	--	x
P2	--	--	x	--	--	x
P3	--	x [0.68]	--	--	--	x
P4	--	--	x	--	--	x
P5	--	--	x	--	--	x
P6	--	--	x	--	--	x
P7	--	--	x	--	--	x
P8	--	x [0.68]	--	--	--	x
P9	--	--	x	--	--	x
P10	--	--	x	--	--	x
P11	--	x [0.60]	--	--	--	x

Table 47: Shared control advisor results.

All the patients, except one, had experience in driving an electric wheelchair. The results show that in that case the aided control was recommended. The other two patients that the system recommended the aided control had some constraints in using the joystick in some directions and thus could also largely benefit from the aided control capabilities.

The experience with the head movements was satisfactory for all the patients. However some of them expressed the opinion that although they like the head movements they are more comfortable with the joystick.

The opinion of the occupational therapists was also requested and was completely coincident with the data analysis system results.

5.2.5 Command Language

In order to generate a command language adapted to a given user several points were taken into account: time efficiency, recognition value of an input sequence and intuitiveness of an input sequence to be associated to a command, as described in Section 4.7.5. The command language evaluation given by the system solution was compared with the command language given by the occupational therapists. Table 48 shows the command language advised by the occupational therapists and by the IDAS. In Table 48, all the directions given by wiimote and joystick refer to the most intuitive and natural directions.

		Command Language for Patients				
Patient	**Evaluation**	**Forward**	**Left**	**Right**	**Back**	**Stop**
P1						
Specialist	4.53	wiimote	joystick	joystick	joystick	joystick
IDAS	4.57	joystick	joystick	joystick	joystick	joystick
P2						
Specialist	4.18	joystick	joystick	joystick	joystick	voice (“stop”)
IDAS	4.85	joystick	joystick	joystick	joystick	voice (“go”)
P3						
Specialist	3.33	voice (“forward”)	wiimote	wiimote	joystick	voice (“stop”)
IDAS	4.51	wiimote	wiimote	wiimote	wiimote	voice (“go”)
P4						
Specialist	4.50	voice (“forward”)	joystick	joystick	joystick	voice (“stop”)
IDAS	4.60	joystick	joystick	joystick	joystick	voice (“stop”)
P5						
Specialist	4.14	voice (“front”)	wiimote	wiimote	joystick	voice (“stop”)
IDAS	4.40	wiimote	wiimote	voice (“turn”)	joystick	voice (“stop”)
P6						
Specialist	4.13	wiimote	joystick	joystick	joystick	joystick
IDAS	4.38	wiimote	wiimote	wiimote	wiimote	wiimote
P7						
Specialist	4.49	voice (“front”)	joystick	joystick	joystick	voice (“stop”)
IDAS	4.60	joystick	joystick	joystick	voice (“back”)	voice (“stop”)
P8						
Specialist	3.51	wiimote	joystick	joystick	joystick	joystick
IDAS	4.20	wiimote	wiimote	wiimote	wiimote	wiimote
P9						
Specialist	3.70	voice (“forward”)	wiimote	wiimote	joystick	voice (“stop”)
IDAS	4.75	joystick	joystick	joystick	joystick	joystick
P10						
Specialist	4.11	voice (“forward”)	voice (“left”)	voice (“right”)	voice (“turn”)	voice (“stop”)
IDAS	4.80	joystick	joystick	voice (“turn”)	joystick	voice (“go”)
P11						
Specialist	4.29	joystick	wiimote	wiimote	joystick	joystick
IDAS	4.30	wiimote	wiimote	wiimote	wiimote	wiimote

Table 48: Command Language advisor results.

In order to compare the results obtained by the specialist and by IDAS, the paired sample t test was applied to the mean of the solution evaluation after verifying the normality using the Kolmogorov-Smirnov test (p value = 0.114). The results show that there are statistical evidences to affirm that the mean of the evaluation of the IDAS is higher than the mean of the evaluation of the command language recommend by the specialist (p value = 0.002).

In particular, from the total of 55 commands from all the 11 patients the data analysis system had exactly the same recommendation as the specialists in 44% of the commands and 53% of the advised commands by the data analysis system use the same input device to produce the command as the ones advised by the specialists.

5.3 Conclusions

This chapter presented all the experiments performed in order to provide scientific evidence that it is possible to create and use a system that can offer patient classification, in the component of their abilities, and automatic adaptation of an intelligent wheelchair for having a more useful and safe manner to drive it. The usefulness of the developed system is clear by analysing the experiments results. All the developed modules such as the simulator, the profiler, the manual and shared controls and the data analysis system for the input device advisor, control advisor and command language allowed having an intelligent wheelchair with a multimodal interface more adapted to the user. The experiments contributed to provide empirical evidence that the system is functional and this has been confirmed by specialists' knowledge that was used to validate the experimental work.

Chapter 6

6. Conclusions and Future Work

This research work intended to develop an automatic patient classification system enabling the automatic adaptation of the IntellWheels prototype to specific users with distinct types of disabilities. The project main outcome was a system capable of automatic configuration of the intelligent wheelchair to the individual patient characteristics, based on real-time assessment of the users' characteristics. The system offers great help for new intelligent wheelchair users since it enables to adapt the wheelchair command language to their own characteristics in a fast and reliable manner. Thus it can be a very valuable tool for individuals suffering from severe handicaps that may not use conventional wheelchairs and even have a great difficulty in using Intelligent Wheelchairs. Several contributions resulted from these work objectives that are clarified in the next section.

6.1 Main Results and Conclusions

The work carried out along this thesis allowed to conduct a series of experiments whose main results enable us to draw several conclusions. In the initial investigation about the state the art of intelligent wheelchairs it was found that the component of adaptation of the wheelchair to the user is a neglected subject in most of the intelligent wheelchair projects. For that reason the concerns related with usability and adaptation of the intelligent wheelchair were always major objectives to be fulfilled on this thesis.

The main conclusion of this work is that an intelligent wheelchair can be automatically adapted to a user, even when this user has severe physical constraints. The adaptation of the interface between the human and the intelligent wheelchair can be performed automatically after a simple protocol to acquire the user profile.

Concerning the multimodal interface developed its importance was highlighted by the experiments with real patients. These experiments showed that some users were unable to use most of the possible driving modes since they were unable to robustly use most of the input modes available. However, they were able to use other inputs and using those inputs they could robustly drive the IW.

The conducted experiments also allowed concluding that the developed simulator is a realistic simulator that enables modelling environments very similar to the patients' typical environments, such as institutions or hospitals. Thus it was a crucial tool enabling to conduct most of the experiments for validating the proposed methodology. In the future it may also be a very important and alternative tool to test and train the users to drive this and other intelligent wheelchairs.

Some conclusions were also taken on how to map the position of joystick regarding the wheelchair wheels' speed based on the performed experiments. It was concluded that it is preferable a more intuitive reaction of the wheelchair to the position of the joystick. Moreover the simple shared control implemented should be used to have a higher safety when a user with physical limitations is driving the intelligent wheelchair. The shared control with adequate aided level for driving the wheelchair can be a usable solution to help the daily life chores of users.

The input device advisor and the input control advisor can also help in the initial decision to select an interface and aided control level for handicapped people. This can help the user and the occupational therapist that normally follows the wheelchairs' users. Moreover, the Data Analysis System generates a command language adapted to the user. This command language can help patients with the most severe cases of disabilities. It was also possible to conclude that the results are similar to the ones recommend by the occupational therapist. Also, the automatically generated command language had better evaluation, combining intuitiveness, recognition and efficiency, than the command language recommended by the specialists.

These findings were made possible due to various contributions of this thesis. The development of the subsystems for data gathering, enabling to collect real-time input information from patients and from the environment and its adaptation to a real wheelchair prototype is also a valuable scientific contribution. The data gathering process creates a data repository of user interaction with wheelchairs that may as well be a valuable contribution. This data repository may be made available to the community, enabling other researchers to develop similar studies.

The data analysis system definition and development brings a new methodology for a human to approach an intelligent wheelchair. More instruments were developed and can be used by health institutions for the phase of recognition of the capabilities of patients, to test and train the users. The *IntellSim* and all the input devices that can be used for the interaction can be easily used before using the real prototypes of the intelligent wheelchair.

The evaluation of the instruments and methodologies was only possible using a set of users, most of them suffering from severe disabilities. These experiments were conducted in close collaboration with ESTSP – Escola Superior de Tecnologia de Saúde do Porto and APPC – Associação do Porto de Paralisia Cerebral. This evaluation was a valuable contribution since only a few Intelligent Wheelchair systems, prototypes or modules were really tested with real patients and none of the prototypes had its interface developed in a flexible manner using knowledge discovery methodologies applied to real user data [7].

6.2 Originality

Although many Intelligent Wheelchair prototypes are being developed in several research projects, around the world, the adaptation of their user interface to the patient is a neglected research topic. Typically, the interfaces are very rigid and adapted to a single user or user group. This project aimed at developing a new concept of Intelligent Wheelchair controlled using high-level commands within a multimodal interface. However, in order to fully control the wheelchair, the user must have a wheelchair interface adapted to his characteristics. Thus, this research work aimed at tackling this problem developing methodologies enabling to dynamically adapt the IW user interface to the user's characteristics.

The experiments with a group of real users suffering from cerebral palsy and having the diagnosis of wheelchair users are also an original contribution. Moreover, besides all are classified as suffering from cerebral palsy, it is possible to affirm that all have different characteristics which make a huge challenge to adapt the interface to a specific user. The methodologies developed enabled users that are unable to use conventional wheelchairs, in a robust and safe manner, to drive the IW wheelchair with success, with just a few minutes of interface adaptation.

6.3 Limitations

The main limitation of this work is the domain in which the experiments were performed. Elderly people and patients suffering from Alzheimer and Parkinson are examples of other potential users of IWs and were not considered in this work. Nevertheless, the group of patients suffering from cerebral palsy aggregates very heterogeneous users which allow confirming the effectiveness of the system that automatically adapts the IW.

Another argument that can be pointed out as being a limitation is that this system was only applied to intelligent wheelchairs. However, the multimodal interface can be applied to control for example a smart environment or a Boccia game ramp using exactly the same methodologies.

6.4 Future Work

The perspectives for future work are related mostly with applying the developed system to other domains and with further improvements of the developed modules and methodologies. In terms of applications several ideas emerged from this work. The multimodal interface and the *IntellSim* simulator with the integrated IDAS can be applied to several other areas such as intelligent buildings or other intelligent electronic devices.

The multimodal interface can be applied and used for several domains:

- In domotics to control the environment of a house with several electronic devices;
- To control smart furniture or other elements in future houses or offices;
- To be applied in the game of the Boccia to fully enable a cerebral palsy user to autonomously play the game. There are categories in Boccia that use a ramp and, on those categories, the player needs an assistant to move this ramp. In order to avoid the presence of the assistance, the ramp could be adapted and the multimodal interface could be used by players not only to control the IW but also to control the ramp.

The *IntellSim* simulator can be used in the future following its main objective of being a training and testing tool. To further extend the simulator, several improvements may be included:

- A simple Boccia game simulator. This would enable cerebral palsy users to play Boccia game at home using the multimodal interface and the simulator. This improvement could be even extended with the development of an electronic Boccia ramp that could be commanded by the multimodal interface. This way a player could use the IW and the ramp to play the entire game without the help of an external element to move the ramp when throwing the balls.
- By introducing in the simulator new features such as some household devices, the environment and the connection of the user with the environment and objects in a house could also be tested with the simulator.

In terms of more scientific perspectives for future work there are also some unexplored issues that can produce interesting fields of analysis, such as:

- Extension of the experimental work to other kind of patients and possible users of an intelligent wheelchair, such as elderly people and patients suffering from Parkinson and Alzheimer;
- Adaptation and development of new tools that enable testing the voice recognition system with the native language of the users;
- Testing new input devices, such as the smartphone with the developed virtual joystick or the switches that are available for the patients suffering from cerebral palsy;
- Development of a robust facial expression recognition and gesture recognition system based mostly in image processing, enabling to use, in a robust manner these inputs in the multimodal interface;

- Development of new paradigms to increase the accuracy of the input devices, such as to better identify the facial expressions and thoughts using the brain computer interface or to avoid the problem of voice recognition by matching sounds instead of words;
- Extend the repository of patients' data and make it available to the scientific community.

All these perspectives for future development are very interesting both in the areas of the engineering and health sciences, such as for example in the fields of Occupational Therapy and Physiotherapy. The areas of Knowledge Discovery, Statistics and Data Mining are also decisive for the exploration of data in these contexts.

Although a long way still follows this research work to enable general use of Intelligent Wheelchairs, the work developed on this thesis is an essential contribution to enable wheelchairs to be generally available, as robust locomotion devices, for any type of patient, having any type of disability.

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Annexes

Scientific Publications: Annex A

Informed Consent for Intelligent Wheelchair Experiments: Annex B

Questionnaire A for sample pre-selection: Annex C

Questionnaire B for Intelligent Wheelchair Experiments: Annex D

Questionnaire C for Joystick Controls Experiments: Annex E

Informed Consent for Joystick Controls Experiments: Annex F

Scientific Activity

Throughout the work carried out during the four years of the Doctoral Program 18 papers were published in journals, book chapters and proceedings of international conferences with referee. Most of the conferences and journals selected for submitting the papers are indexed in ISI Web of Knowledge through the ISI-Proceedings index and Scopus from Elsevier. This annex contains a brief overview of each of these papers and their contribution for acquiring the skills needed for conducting the proposed thesis.

Journals and Book Chapters

1. Brígida Mónica Faria; Gladys Castillo, Nuno Lau, Luís Paulo Reis, *Classification of FC Portugal Robotic Soccer Formations: A comparative Study of Machine Learning Algorithms*, Robotica Magazine, n. 82, 1º Trimestre, pp 4 - 9, 2011, ISSN: 0874-9019

This paper was selected as one of the best papers of the 10th Conference on Mobile Robots and Competitions, held at the Instituto Politécnico de Leiria to be published as an extended revised paper in the Robotica Journal. This is one of the main technical publications in Portugal in the field of Robotics and Automation. The paper describes the application of data mining algorithms in order to classify robotic soccer formations used by the FC Portugal robotic soccer team.

2. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, *Knowledge Discovery and Multimodal Inputs for Driving an Intelligent Wheelchair*, International Journal of Knowledge Discovery in Bioinformatics, Vol. 2, n. 4, pp 18-34, 2011, DOI: 10.4018/jkdb.2011100102.

This paper is an extension of the paper published in the IEEE International Conference on Data Mining 2012, Biological Data Mining and its Applications in Healthcare Workshop selected to be published in the International Journal of Knowledge Discovery in Bioinformatics. This paper describes the motor disorders in cerebral palsy associated with deficits of perception, cognition, communication and behaviour which can affect the autonomy and independence. The interface between the user and an intelligent wheelchair can be done with several input devices such as Joysticks, Microphones and Brain Computer Interfaces (BCI). This paper presents an approach to expand the use of a brain computer interface for driving an intelligent wheelchair by patients suffering from cerebral palsy. The ability with the joystick, head movements and voice inputs were also tested and the best possibility for driving the wheelchair is given to a specific user.

3. Luís Paulo Reis, Romina Neves, Pedro Abreu, Brígida Mónica Faria, *Sistema Inteligente para Auxílio na Seleção e Execução de Tarefas num Jogo Social*, Computer Science and Engineering, Julho, 2012, pp. 74-81, DOI:10.5923/j.computer.20120001.10.

This paper describes the development of an intelligent system able to effectively assist the player when playing a social game. The use of the implemented system ensures greater progress in the game, because there is a decrease in the time spent in performing the tasks enabling the user to focus on the strategies for advancing in the game.

4. João Lobato Oliveira, Luis Paulo Reis, Brígida Mónica Faria, *An Empiric Evaluation of a Real-Time Robot Dancing Framework based on Multi-Modal Events*, TELKOMNIKA Indonesian Journal of Electrical Engineering Vol 10, n. 8, Dezembro 2012.

This paper describes and assesses a framework for robot dancing edutainment applications. The proposed robotics architecture enables the definition of choreographic compositions, which result on a conjunction of reactive dancing motions in real-time response to multi-modal inputs. These inputs are shaped by three rhythmic events (representing soft, medium, and strong musical note-onsets), different dance floor colours, and the awareness of the surrounding obstacles. This layout was applied to a Lego-NXT humanoid robot, built with two Lego-NXT kits, and running on a hand-made dance stage. It was performed an empirical evaluation over the overall robot dancing performance made to a group of students after a set of live demonstrations. This evaluation validated the framework's potential application in edutainment robotics and its ability to sustain the interest of the general audience by offering a reasonable compromise between musical-synchrony, animacy and dance performance's variability.

5. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, João Couto Soares, Sérgio Vasconcelos, *Patient Classification and Automatic Configuration of an Intelligent Wheelchair*, Communications in Computer and Information Science 358, Springer-Verlag, pp. 268-282, 2013. [ISI] [Scopus]

This paper is an extension of the paper from the ICAART 2012 that was selected as one of the best papers of the conference to be published in a book chapter of the Springer-Verlag.

6. Brígida Mónica Faria, Sérgio Vasconcelos, Luís Paulo Reis, Nuno Lau, *Evaluation of Distinct Input Methods of an Intelligent Wheelchair in Simulated and Real Environments: A Performance and Usability Study*. Assistive Technology: The Official Journal of RESNA (Rehabilitation Engineering and Assistive Technology Society of North America), USA, Taylor & Francis, DOI: 10.1080/10400435.2012.723297, To appear, Junho 2013. [ISI] [Scopus]

This paper focuses on evaluating the usability of an Intelligent Wheelchair (IW) in both real and simulated environments. A quasi-experimental design was applied including a deterministic sample with a questionnaire that enabled to apply the System Usability Scale. The subjects were divided in two independent samples: the experiment with the IW in a simulated environment and individuals performing the experiment with a real IW. The main conclusion achieved by this study is that the usability of the Intelligent Wheelchair in a real environment is higher than in the simulated environment. However there were not statistical evidences to affirm that there are differences between the real and simulated wheelchairs in terms of safety and control. Also, most of users considered the multimodal way of driving the wheelchair very practical and satisfactory. Thus, it may be concluded that the multimodal interfaces enables very easy and safe control of the IW both in simulated and real environments.

7. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, *Adapted Control Methods for Cerebral Palsy users of an Intelligent Wheelchair*, 13th International Conference on Autonomous Robot Systems and Competitions (selected and extended papers), Journal of Intelligent and Robotics Systems, Springer, To be submitted [ISI] [Scopus]

This paper is an extension of the paper *Manual, Automatic and Shared Methods for Controlling an Intelligent Wheelchair: Adaptation to Cerebral Palsy Users* from the 13th International Conference on Autonomous Robot Systems and Competitions that was selected as one of the best papers of the conference to be submitted for the Journal of Intelligent and Robotics Systems, Springer.

8. Brígida Mónica Faria, Sérgio Vasconcelos, Luís Paulo Reis, Nuno Lau, *Multimodal Interface for an Intelligent Wheelchair*, Journal of Disability and Rehabilitation: Assistive Technology, Submitted. [ISI] [Scopus]

This paper presents the specification and development of the multimodal interface, as a component of the Intelligent Wheelchair (IW). The developed prototype combines several input modules, allowing the control of the wheelchair through flexible user defined input sequences of distinct types (voice inputs, facial expressions, head movements and joystick). To validate the effectiveness of the prototype, two experiments were performed with a number of individuals who tested the system firstly by driving a simulated wheelchair in a virtual environment. The second experiment was performed using the real IW prototype. The results achieved proved that the multimodal interface may be successfully used by people, due to the interaction flexibility it provides.

International Conferences

9. Marco Silva, Luís Paulo Reis, Armando Sousa, Brígida Mónica Faria, António Pedro Costa, *iiBOARD – Development of a Low-Cost Interactive Whiteboard using the Wiimote Controller*, Proceedings

of the Fourth International Conference on Computer Graphics Theory and Applications, pp. 337-344, 5-8 de Fevereiro, 2009, Lisboa, Portugal, ISBN: 978-989-8111-67-8 [ISI] [Scopus]

This paper describes the steps taken for the development of an innovative low-cost interactive whiteboard based on the Wii Remote command of the Nintendo Wii video-game console - iiBOARD. Although this command is very inexpensive it has an infrared camera and supports Bluetooth communication. The system control is based on a wireless device, based on infrared emitters, which supports most of the mouse events. A complete whiteboard application was also developed using Borland Delphi for Windows. This application may be used with either one or two Wiimotes and has a very simple and efficient calibration method. The application also includes viewing capabilities of some of the Wiimote characteristics, as well as a flexible Notebook to increase its range of possible uses. The PhD student work was mainly concerned with conducting a questionnaire to a set of whiteboard users and analysing the results. These results showed that the users had a very positive acceptance of the inexpensive iiBOARD solution proposed. The type of technology used, survey conducted and result analysis process of these work is very similar to the ones planned for this research proposal.

10. Brígida Mónica Faria, Nuno Lau, Luís Paulo Reis, *Classification of Facial Expressions using Data Mining and Machine Learning Algorithms; CISTI 2009* – 4ª Conferência Ibérica de Sistemas e Tecnologias de Informação, Sistemas e Tecnologias de Informação, edited by Álvaro Rocha et al., Edição APPACDM, p. 197-202, June 17-20, 2009, Póvoa de Varzim, Portugal, ISBN: 978-989-96247-0-2 [ISI] [Scopus]

This paper was based on the work developed for Seminários and includes a simple methodology and some experimental work using WEKA and several machine learning algorithms for facial expressions detection. The paper presents a comparative study of three algorithms for classification basic facial expressions: OneR, Naïve Bayes and Sequential Minimal Optimization (SMO). The results achieved identifying faces and facial expressions of 983 faces in the known BioID database, enabled to conclude that SMO is able to achieve better results in recognizing individuals and basic facial expressions.

11. Brígida Mónica Faria, Nuno Lau, Luís Paulo Reis, *Applications of Machine Learning Algorithms for Individual Recognition and Facial Expressions Classification*; VipImage 2009 – Thematic on Computacional Vision and Medical Image Processing, edited by João Tavares & Natal Jorge, Taylor & Fancis Group, pp 233-239, October 14-16, 2009, Porto, Portugal, ISBN: 978-0-415-57041-1 [ISI] [Scopus]

The previous work was further extended by developing additional experimental work using the RapidMiner and several new machine learning algorithms for recognizing not only the individuals but also some characteristics of their facial expressions. With this additional work it was possible to understand the behaviour and accuracy of the models produced by the algorithms implemented. Also it was analysed how it is possible to enhance the facial expression classification by using some coordinates of simple additional points. This additional work had also the objective of acquiring experience that in the future can be applied and incorporated in the IntellWheels project.

12. Brígida Mónica Faria, Rui Pimenta, José Moreira, *Projects of Fisioterapia and Terapia Ocupacional: A Classification Approach using Text Mining in R*, CISTI 2009 – 4ª Conferência Ibérica de Sistemas e Tecnologias de Informação, Sistemas e Tecnologias de Informação, edited by Álvaro Rocha et al., Edição APPACDM, p. 367-372, June 17-20, 2009, Póvoa de Varzim, Portugal, ISBN: 978-989-96247-0-2 [ISI] [Scopus]

As part of the module Decision Support Systems the area of Text Mining was explored using clustering and a comparative study of two algorithms for classification reports: K-Nearest Neighbour and Support Vector Machine (SVM). The results achieved consisted in identifying final degree projects' reports of Fisioterapia and Terapia Ocupacional in the context of the Escola Superior de Tecnologia da Saúde do Porto.

13. Brígida Mónica Faria; Beatriz Sousa Santos, Nuno Lau, Luís Paulo Reis, *Data Visualization for Analyzing Simulated Robotic Soccer Games*, IVAPP - International Conference on Information Visualization Theory and Applications, pp 161-168, May 17-21, 2010, Angers, França, ISBN: 978-989-674-027-6 [ISI] [Scopus]

The frequency of the module of Data Visualization was an opportunity to obtain the knowledge about several visualization techniques, for instance in the area of Visual Data Mining and by using them is possible to absorb large amounts of visual information and find patterns in it. In this paper it is presented an approach to the visualization of simulated robotic soccer games using the RapidMiner software package. Various visualizations were developed using Andrew´s Curves, Survey Plots, several types of Parallel Coordinate visualizations and Radial Coordinate Visualizations. These visualizations enabled to take some interesting conclusions about the differences between games of FC Portugal robotic soccer team using different formations and against distinct opponents. The Visual Data Mining can also be used to identify patterns in patients attributes.

14. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, Gladys Castillo, *Machine Learning Algorithms applied to the Classification of Robotic Soccer Formations and Opponent Teams*, IEEE - International Conference on Cybernetics & Intelligent Systems, pp 344 - 349, 28-30 Junho, 2010, Singapore, ISBN: 978-1-4244-6501-9 [ISI] [Scopus]

This paper presents a concrete application of several Machine Learning (ML) techniques in the identification of the opponent team and automatic detection of some of its characteristics and also on the classification of robotic soccer formations. The experimental tests performed, using three distinct datasets, enabled us to conclude that the Support Vector Machines (SVM) technique allows classifying complex data with higher accuracy than the k-Nearest Neighbour and Neural Networks. The very good accuracy revealed by the SVM technique, even with small data sets, enables the use this ML technique in real games for performing online opponent and formation classification. This work enabled to test several machine learning algorithms for solving several complex classification problems.

15. Brígida Mónica Faria, *Data Analysis of Three Procedures for Constructing Semiconductors: Mold, Solder Ball and Singulation*, CISTI 2011, pp 509 - 514, 15-18 Junho, 2011, Chaves, ISBN: 978-989-96247-4-0 [ISI] [Scopus]

This paper focuses in the methods to data analysis of real data from the process of semiconductor manufacturing. Statistical approaches were applied to detect differences in the performance of four teams of a company in terms of time and failures presented in three processes of the production: Mold, Solder Ball Attach and singulation. From the analysis it was possible to conclude that there were differences in terms of behaviour of the teams. The multivariate statistical analysis methods used were clustering and Principal Component Analysis.

16. Brígida Mónica Faria, Sérgio Vasconcelos, Luís Paulo Reis, Nuno Lau, *A Methodology for Creating Intelligent Wheelchair Users' Profiles*, ICAART 2012, pp 171-179, 6-8 Fevereiro, 2012, Algarve, ISBN: 978-989-8425-95-9 [ISI] [Scopus]

This paper describes the methodology used for creating a user profile for the intelligent wheelchair. The process and the implementation in the multimodal interface were described and the preliminary experiments and results were also presented. This work enabled to confirm the possibility of using the profile strategy for presenting the most suitable interface for a user to drive the intelligent wheelchair.

17. Brígida Mónica Faria, Luís Ferreira, Luís Paulo Reis, Nuno Lau, Marcelo Petry, João Couto Soares, *Manual Control for Driving an Intelligent Wheelchair: A Comparative Study of Joystick Mapping Methods*, Progress, challenges and future perspectives in navigation and manipulation assistance for robotic wheelchairs workshop, IEEE/RSJ International Conference on Intelligent Robots and Systems 2012, Vila Moura, Algarve, 7-12 Outubro, 2012, ISBN: 978-972-8822-26-2.

This paper describes the implementation of several joystick mappings in an intelligent wheelchair (IW) prototype. Experiments were performed in a realistic simulator using 25 users with distinct driving abilities. The users had 6 different joystick control mapping methods and for each user the usability and preference order was measured. The results achieved show that a linear mapping, with appropriate parameters, between the joystick's coordinates and the wheelchair wheel speeds is preferred by the majority of the users.

18. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, *Cerebral Palsy EEG signals Classification: Facial Expressions and Thoughts for Driving an Intelligent Wheelchair*, IEEE International Conference on Data Mining 2012, Biological Data Mining and its Applications in Healthcare Workshop, Bruxelas, pp 33-40, Dezembro, 2012, ISBN: 978-1-4673-5164-5 10-13. [Scopus]

This paper presents an approach to expand the use of a brain computer interface for driving an intelligent wheelchair by patients suffering from cerebral palsy. The approach was based on appropriate signal pre-processing based on Hjorth parameters, a forward approach for variable selection and several data mining algorithms for classification such as naive Bayes, neural networks and support vector machines. Experiments were performed using 30 individuals suffering from IV and V degrees of cerebral palsy on the Gross Motor Function (GMF) measure. The results achieved showed that the pre-processing and variable selection methods were effective enabling to improve the results of a commercial BCI product by 57%. With the developed system it was also possible for users to perform a circuit in a simulated environment using just facial expressions and thoughts.

19. Brígida Mónica Faria, Luís Paulo Reis, Nuno Lau, *Manual, Automatic and Shared Methods for Controlling an Intelligent Wheelchair: Adaptation to Cerebral Palsy Users*, 13th International Conference on Autonomous Robot Systems and Competitions, 24-25 April, 2013, To appear.

This paper presents three distinct control methods which were implemented in the IW: manual, shared and automatic. Experiments were performed, using the *IntellSim* simulator, with real users suffering from cerebral palsy in order to validate the approach. These experiments enabled to conclude which were the best shared control methods to implement on the IW. The experiments also revealed the importance of using shared (aided) controls for users with severe disabilities. The patients still felt having complete control over the wheelchair movement when using a shared control at a 50% level and thus this control type was very well accepted and should be used in intelligent wheelchairs since it is able to correct the direction in case of involuntary movements of the user but still gives him a sense of complete control over the IW movement.

20. Brígida Mónica Faria, Sofia Carmo Teixeira, Joaquim Faias, Luís Paulo Reis, Nuno Lau, *Intelligent Wheelchair Simulator for Users' Training: Cerebral Palsy Children's Case Study*, 8th Iberian Conference on Information Systems and Technologies, 19-22 April, 2013, To appear [ISI] [Scopus]

The aim of this study was to verify if the exigency of using the simulator of the IntellWheels project is adequate to the skills of children with cerebral palsy. A group study case was performed using children with cerebral palsy classified in the levels IV and V of the Gross Motor Function Classification System, aged between 6 and 12 years old. The user's performance in a wheelchair driving game using the Joystick and the Wiimote (for head movements' recognition) and the users' opinions about the system were studied. Results suggest that the system matches the children skills and it was verified that it was easier to drive the wheelchair with the joystick for most of the participants. Generally, the participants presented positive reactions, showing themselves satisfied with the experiment and convicted about the wheelchair future usability.

Informed Consent
Declaração de consentimento informado

Conforme alei 67/98 de 26 de Outubro e a "Declaração de Helsínquia" da Associação Médica Mundial (Helsínquia 1964; Tóquio 1975; Veneza 1983; Hong Kong 1989; Somerset West 1996, Edimburgo 2000; Washington 2002, Tóquio 2004, Seul 2008)

Designação do Estudo: IntellWheels - Cadeira de Rodas Inteligente com Interface Multi-Modal Flexível

Eu, ____abaixo-assinado (ou Eu, ____(nome completo do representante legal do indivíduo participante do estudo), na qualidade de representante legal de ____(nome completo do indivíduo participante do estudo)). Fui informado de que o Estudo de Investigação acima mencionado se destina a obter dados sobre o desempenho na condução de uma cadeira de rodas inteligente (CRI) recorrendo a uma inteface multimodal. Esta interface permite conduzir a CRI utilizando diversos inputs, tais como: movimentos de cabeça, comandos de voz, através de uma *brain computer interface*, *joystick e botões do joystick*.

Sei que neste estudo está prevista a realização de testes num simulador e preenchimento de um questionário tendo-me sido explicado em que consistem quais os seus possíveis efeitos.

Foi-me garantido que todos os dados relativos à identificação dos participantes neste estudo são confidenciais e que será mantido o anonimato.

Sei que posso recusar-me a participar ou interromper a qualquer momento a participação no estudo, sem nenhum tipo de penalização por este facto. (ou Sei que posso recusar-me a autorizar a participação ou interromper a qualquer momento a participação no estudo, sem nenhum tipo de penalização por este facto).

Compreendi a informação que me foi dada, tive oportunidade de fazer perguntas e as minhas dúvidas foram esclarecidas.

Aceito participar de livre vontade no estudo acima mencionado (ou Autorizo de livre vontade a participação daquele que legalmente represento no estudo acima mencionado).

Também autorizo a divulgação dos resultados obtidos no meio científico, garantindo o anonimato.

Data	Assinatura
___/___/_____	____

Questionário A – Pre-seleção

Identificação

1.Nome:____

2.Idade: ____ 3.Género: F□ M □ 4. Diagnóstico:________ 5. Nível da GMFM:_______

6. Utilizador da cadeira de rodas Sim □ Não □

6.1 Se sim, qual o tipo de cadeira de rodas.

Manual □ Elétrica □ Inteligente □ Outra □ Qual?___________

6.1.1 Há quantos anos utiliza a cadeira de rodas?__________________

6.1.2 É autónomo na utilização da cadeira de rodas? Sim □ Não □

6.1.3 É independente na utilização da cadeira de rodas? Sim □ Não □

6.2 Se não, é potencial utilizador da cadeira de rodas? Sim □ Não □

6.2.1 Qual o tipo de cadeira de rodas mais provável?

Manual □ Elétrica □ Inteligente □ Outra □ Qual?___________

7. Pratica Boccia? Sim □ Não □ 7.1 Se sim, há quantos anos?__________

Profile

<u>Gamepad</u>
Ser capaz de realizar sequências, ao premir botões incorporados no joystick.

Sim □ Não □

<u>Comandos de voz</u>
Ser capaz de realizar vocalizações com propósito.

Sim □ Não □

<u>Joystick</u>
Ser capaz de direcionar o movimento como pretendido.

Sim □ Não □

<u>WiiMote Movimentos de cabeça</u>
Ter controlo de cabeça para direcionar o movimento como pretendido.

Sim □ Não □

<u>BCI</u>

Expressões faciais	Sim	Não
Piscar o olho esquerdo		
Piscar olho direito		
Franzir a testa		
Ranger os dentes		
Sorri para a direita		
Sorrir		
Sorrir para a esquerda		
Piscar ambos os olhos		

Outras expressões faciais: ____

Interface de controlo para a fase de teste no simulador:___________________

Questionário B – Usabilidade da Cadeira de Rodas Inteligente (CRI) (Simulador)

Através deste questionário pretende-se obter informações sobre a utilização da Cadeira de Rodas Inteligente. Os dados fornecidos serão tratados de forma agregada bem como será mantida a confidencialidade. Agradecemos a disponibilidade e a colaboração.

1. Identificação do Utilizador.

1.1. Idade: ______________ 1.2. Sexo: Feminino ☐ Masculino ☐

1.3. Peso (em kg): _____________ 1.4. Altura (cm): ______________

1.5. Apresenta alguma dificuldade motora? Sim ☐ Não ☐

1.5.1 Se sim qual(ais)? ___________________________________

1.6. Apresenta alguma dificuldade cognitivas? Sim ☐ Não ☐

1.6.1 Se sim qual(ais)? ___________________________________

1.7. Indique o seu caso:

1.7.1. Destro? Sim ☐ Não ☐ 1.7.2. Daltónico? Sim ☐ Não ☐

1.8. Assinale o seu nível de escolaridade (ou que frequenta):

1º Ciclo		Bacharelato	
2º Ciclo		Licenciatura	
3º Ciclo		Mestrado	
Secundário		Doutoramento	

1.9. Qual a frequência de utilização de Jogos de Vídeo?

Instruções: Cada opção de resposta expressa uma atitude numa escala de 1 a 5, onde:

1 = Nunca, 2 = Raramente, 3 = Às vezes, 4 = Muitas vezes, 5 = Sempre

Para cada questão deve tentar comparar a sua opinião com cada uma das opções de resposta, marcando com um x na opção mais exacta.

	1	2	3	4	5
1.9.1. Costumo jogar jogos de vídeo.					
1.9.2. Costumo utilizar comandos de jogos de vídeo (tipo wii, playstation).					
1.9.3. Costumo utilizar o joystick.					

2. Fez a sessão de *Profiling*? Sim ☐ Não ☐

3. Usabilidade e Segurança da Cadeira de Rodas Inteligente (Simulador).
Instruções: Cada opção de resposta expressa uma atitude numa escala de 1 a 5, onde:
1 = Discordo totalmente, 2 = Discordo, 3 = Indiferente, 4 = Concordo, 5 = Concordo totalmente
Para cada questão deve tentar comparar a sua opinião com cada uma das opções de resposta, marcando com um x na opção mais exacta.

Tradução da Escala SUS ***(System Usability Scale)***	1	2	3	4	5
3.1. Penso que gostaria de utilizar a CRI com frequência.					
3.2. Achei que a CRI é desnecessariamente complexa.					
3.3. Penso que a CRI é de fácil utilização.					
3.4. Penso que iria necessitar de apoio de um técnico para ser capaz de utilizar a CRI em pleno.					
3.5. Penso que as diversas funções da CRI foram bem integradas.					
3.6. Penso que a CRI tem muitas incoerências.					
3.7. Penso que a maioria dos utilizadores aprenderia facilmente a utilizar a CRI.					
3.8. Penso que a CRI é muito complicada de utilizar.					
3.9. Senti-me confiante na utilização da CRI.					
3.10. Penso que ainda necessitaria de aprender muitas funcionalidades da CRI.					
Segurança	1	2	3	4	5
3.11. Senti-me seguro na condução da CRI.					
3.12. Senti que tive controlo da CRI.					
3.13. É fácil conduzir a CRI em espaços estreitos.					
3.14. Conduzir a CRI não necessita muita atenção.					

4. Utilização dos Meios de Controlo da Cadeira de Rodas Inteligente (Simulador).
Instruções: Cada opção de resposta expressa o nível de satisfação numa escala de 1 a 5, onde:
1 = Muito Insatisfeito, 2 = Insatisfeito, 3 = Indiferente, 4 = Satisfeito, 5 = Muito Satisfeito
Para cada questão deve tentar comparar a sua opinião com cada uma das opções de resposta, marcando com um x na opção mais exacta.

4.1. Indique o **nível de satisfação relativamente ao tipo de controlo da CRI**.	1	2	3	4	5
4.1.1. Utilização do joystick no modo manual.					
4.1.2. Utilização do gamepad (modo de alto nível).					

4.1.3. Utilização dos comandos de voz.					
4.1.4. Utilização dos movimentos de cabeça.					
4.1.5. Utilização da Brain Computer Interface (BCI).					
4.1.6. Utilização de modo integrada de todos os comandos.					

4.2. Indique quais as falhas/incoerências que encontrou durante a realização da experiência com CRI:

____

____

____

4.3. Indique quais as principais dificuldades que sentiu durante a realização da experiência com CRI:

____

____

____

4.4. Indique possíveis alterações de melhoria do Simulador:

____

____

____

5. Interface Multimodal.
Instruções: Cada opção de resposta expressa o nível de satisfação numa escala de 1 a 5, onde:

1 = Discordo totalmente, 2 = Discordo, 3 = Indiferente, 4 = Concordo, 5 = Concordo totalmente

Para cada questão deve tentar comparar a sua opinião com cada uma das opções de resposta, marcando com um x na opção mais exacta.

	1	2	3	4	5
5.1. A Interface Multimodal facilitou a informação sobre o tipo de comandos que estava a utilizar.					
5.2. A Interface Multimodal ajudou na criação de sequências de comando.					

5.3. Indique possíveis alterações de melhoria da Interface Multimodal:

____

____

____

6. Fadiga e Frustração.
Instruções: Cada opção de resposta expressa uma atitude numa escala de 1 a 5, onde:

1 = Discordo totalmente, 2 = Discordo, 3 = Indiferente, 4 = Concordo, 5 = Concordo totalmente

Para cada questão deve tentar comparar a sua opinião com cada uma das opções de resposta, marcando com um x na opção mais exacta.

6.1. Fadiga/Frustração da **BCI**	1	2	3	4	5
6.1.1. Senti-me fatigado depois da experiência com a BCI.					
6.1.2. Senti-me frustrado com a experiência da BCI					
6.1.3. Senti-me aborrecido com a experiência da BCI.					
6.1.4. Pensar nas acções é cansativo.					
6.1.5. Fazer as acções é cansativo.					
6.1.6. É preciso muita concentração para pensar nas acções.					
6.1.7. É preciso muita concentração para fazer as acções.					
6.2. Fadiga/Frustração dos **Movimentos de Cabeça**	1	2	3	4	5
6.2.1. Senti-me fatigado depois da experiência.					
6.2.2. Senti-me frustrado com a experiência					
6.2.3. Senti-me aborrecido com a experiência.					
6.2.4. Pensar nas acções é cansativo.					
6.2.5. Fazer as acções é cansativo.					
6.2.6. É preciso muita concentração para pensar nas acções.					
6.2.7. É preciso muita concentração para fazer as acções.					
6.3. Fadiga/Frustração dos **Comandos de Voz**	1	2	3	4	5
6.3.1. Senti-me fatigado depois da experiência.					
6.3.2. Senti-me frustrado com a experiência					
6.3.3. Senti-me aborrecido com a experiência.					
6.3.4. Pensar nas acções é cansativo.					
6.3.5. Fazer as acções é cansativo.					
6.3.6. É preciso muita concentração para pensar nas acções.					
6.3.7. É preciso muita concentração para fazer as acções.					
6.4. Fadiga/Frustração do **Joystick**	1	2	3	4	5
6.4.1. Senti-me fatigado depois da experiência.					
6.4.2. Senti-me frustrado com a experiência					
6.4.3. Senti-me aborrecido com a experiência.					
6.4.4. Pensar nas acções é cansativo.					
6.4.5. Fazer as acções é cansativo.					

6.4.6. É preciso muita concentração para pensar nas acções.					
6.4.7. É preciso muita concentração para fazer as acções.					
6.5. Fadiga/Frustração dos **Botões**	1	2	3	4	5
6.5.1. Senti-me fatigado depois da experiência.					
6.5.2. Senti-me frustrado com a experiência					
6.5.3. Senti-me aborrecido com a experiência.					
6.5.4. Pensar nas acções é cansativo.					
6.5.5. Fazer as acções é cansativo.					
6.5.6. É preciso muita concentração para pensar nas acções.					
6.5.7. É preciso muita concentração para fazer as acções.					

6.6. Indique por ordem crescente de dificuldade (1 – Mais Fácil até 5 – Mais Difícil) o tipo de comando utilizado:

☐ Comandos de voz ☐ Movimentos de cabeça ☐ Joystick (modo manual)

☐ Brain Computer Interface ☐ Gamepad (modo alto nível)

6.7. Indique por ordem crescente de preferência (1 – Gosto Muito até 5 – Gosto Pouco) o tipo de comando utilizado:

☐ Comandos de voz ☐ Movimentos de cabeça ☐ Joystick (modo manual)

☐ Brain Computer Interface ☐ Gamepad (modo alto nível)

IntellWheels Joystick Controls - Adapted from Computer System Usability Questionnaire

User Identification (Identificação do Utilizador)

1 - Name (Nome) ____

2 - Age (Idade) ____

3 - Gender (Sexo) ◯ Male ◯ Female

4 - Dominant Hand (Mão dominante) ◯ Left ◯ Right

5 - School Level (Nível de Escolaridade)

◯ Illiterate (Analfabeto)
◯ Elementary School (1º Ciclo)
◯ Middle School (2º e 3º Ciclos)
◯ High School (Secundária)
◯ BSc (Licenciatura)
◯ MSc (Mestrado)
◯ PhD (Doutoramento)

Video games (vídeo-jogos)

6 - I play video games (Eu jogo vídeo-jogos)

◯ 1 – Never ◯ 2 – Rarely ◯ 3 – Sometimes ◯ 4 – Often ◯ 5 – Always

7 - I usually use commands of video games (like wii, playstation) (Eu costumo utilizar comandos de vídeo-jogos)

◯ 1 – Never ◯ 2 – Rarely ◯ 3 – Sometimes ◯ 4 – Often ◯ 5 – Always

8 - I usually use the joystick (Eu costumo utilizar joystick)

◯ 1 – Never ◯ 2 – Rarely ◯ 3 – Sometimes ◯ 4 – Often ◯ 5 – Always

Control (Controlo)

◯ **Control A** ◯ **Control B** ◯ **Control C** ◯ **Control D** ◯ **Control E** ◯ **Control F**

1 - Overall, I am satisfied with how easy it is to use this control (De uma maneira geral estou satisfeito com a facilidade de utilização deste controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

2 - It was simple to use this control (Foi fácil utilizar este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

3 - I can effectively complete this task using this control (Eu consigo efectivamente completar esta tarefa utilizando este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

4 - I am able to complete this task quickly using this control (Eu posso terminar rapidamente esta tarefa utilizando este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

5 - I am able to efficiently complete this task using this control (Eu posso completar eficientemente esta tarefa utilizando este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

6 - I feel comfortable using this control (Eu sinto-me confortável a utilizar este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

7 - It was easy to learn to use this control (Foi fácil aprender a utilizar este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

8 - Whenever I make a mistake using the control, I recover easily and quickly (Quando cometia algum erro utilizando este controlo, eu recuperei fácil e rapidamente)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

9 - Overall, I am satisfied with this control (De uma maneira geral estou satisfeito com este controlo)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

10 - I felt I had control of the wheelchair (Senti que tive controlo da cadeira de rodas)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

11 - It is easy to drive the wheelchair in narrow spaces (É fácil conduzir a cadeira de rodas em espaços estreitos)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

12 - Drive the wheelchair do not need too much attention (Conduzir a cadeira de rodas não necessita muita atenção)

◯ 1 - Strongly Disagree ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7 - Strongly Agree

Controls Preference (Controlos Preferência)

Re-order (drag and drop) by your preference (1 - Best to 6 - Worst)

______ Control A
______ Control B
______ Control C
______ Control D
______ Control E
______ Control F

TERMO DE CONSENTIMENTO INFORMADO

Declaração de consentimento informado

Conforme alei 67/98 de 26 de Outubro e a "Declaração de Helsínquia" da Associação Médica Mundial (Helsínquia 1964; Tóquio 1975; Veneza 1983; Hong Kong 1989; Somerset West 1996, Edimburgo 2000; Washington 2002, Tóquio 2004, Seul 2008)

Designação do Estudo: IntellWheels - Cadeira de Rodas Inteligente com Interface Multi-Modal Flexível

Eu, ____abaixo-assinado fui informado que o Estudo de Investigação acima mencionado se destina a obter dados sobre o desempenho e satisfação na condução de uma cadeira de rodas inteligente (CRI) recorrendo a um joystick.
Sei que neste estudo está prevista a realização de testes num simulador e preenchimento de um questionário tendo-me sido explicado em que consistem e quais os seus possíveis efeitos.
Foi-me garantido que todos os dados relativos à identificação dos Participantes neste estudo são confidenciais e que será mantido o anonimato.
Sei que posso recusar-me a participar ou interromper a qualquer momento a participação no estudo, sem nenhum tipo de penalização por este facto.
Compreendi a informação que me foi dada, tive oportunidade de fazer perguntas e as minhas dúvidas foram esclarecidas.
Aceito participar de livre vontade no estudo acima mencionado.
Também autorizo a divulgação dos resultados obtidos no meio científico, garantindo o anonimato.

Data	Assinatura
___/___/_____	____

Nome do Investigador Responsável e Contacto: Luís Paulo Reis (lpreis@dsi.uminho.pt).